GLACIER OUTBURST FLOODS IN THE PACIFIC NORTHWEST

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Abstract.—Glacier outburst floods, not uncommon in the Pacific Northwest in late summer or fall, are sometimes triggered by heavy rain but may occur even during a rainless period. Associated mudflows often compound the destruction downstream. Outburst floods are particularly hazardous at Mount Rainier, Wash., where debris flows are reported to occur at a rate of one in 3–10 years. Several floods witnessed at Mount Rainier were much larger than expected from direct storm runoff or release of water temporarily impounded by landslides. The principal source of those floods is believed to have been the large volumes of water that are stored at times within and beneath glaciers. At present there is no known way of predicting glacier outburst floods. Conceivably, their imminence might be indicated by measurements of englacial water pressure, and their potential size would be indicated by determinations of the volume of water stored in glaciers.

Glacier outburst floods, sometimes referred to by the Icelandic term "jökulhlaups," are a common occurrence at many places where there are active temperate glaciers. A jökulhlaup can be an awesome spectacle—an impressive display of powerful forces of nature. When a large amount of water is suddenly released at the head of a steep mountain valley containing loose alluvial and glacial deposits, the results can be very destructive. In this article some eyewitness accounts are given of floods that were affected by, or were the direct result of, glacier outbursts in the Pacific Northwest. Most of these floods were observed on the south side of Mount Rainier, Wash. (fig. 1). Crandell and Mullineaux (1967, p. 20) estimate that debris flows and floods not caused by volcanic activity probably have occurred at Mount Rainier at a rate of one in 3–10 years.

DESCRIPTION OF OUTBURST FLOODS

Nisqually River

In October 1926, a flood occurred on the upper Nisqually River during the first heavy rain at the end of the summer. The old Nisqually Glacier bridge was damaged so severely that it was temporarily closed. There is no record of the size of the flood, but on the basis of the reported damage to the bridge the flow must have been at least several thousand cubic feet per second (100–200 cubic meters per second). As the drainage area at the Nisqually Glacier bridge is only 6.2 square miles (16 square kilometers), the unit runoff during the peak flow was probably on the order of 1,000 cubic feet per second per square mile (11 $m^3/sec/km^2$). Direct storm runoff of such intensity is exceedingly rare in the Pacific Northwest (see later discussion of storm runoff), and it is suggested, therefore, that a glacier outburst was likely a contributing factor in the flood of October 1926. A concrete bridge, completed soon after the old bridge was damaged, was destroyed by an outburst flood in October 1932.

The Nisqually Glacier jökulhlaup of October 14, 1932, was the first of several that are known to have been witnessed in Mount Rainier National Park. The following description of the flood is from a monthly report of activities in the park, prepared by Park Superintendent O. A. Tomlinson:

> The outstanding occurrence of the month was the flood or "wash" from the Nisqually Glacier about noon, October 14 which destroyed the Nisqually River reinforced concrete bridge. Following several days' heavy rains a landslide above a series of three or four catch basins on the lateral moraine and or the glacier itself released large quantities of accumulated water which swept down over the glacier and down stream carrying away the bridge which was one-half mile below the end of the ice. The landslide occurred slightly more than a quarter mile above the snout of the glacier. Millions of gallons of water were suddenly released carrying rock and debris from the top and end of the glacier. By the time this moving mass reached the bridge it was approximately 25 feet high and 150 feet wide. The force of the impact carried away the entire center span which was of reinforced concrete 55 feet long and 27 feet wide with massive railings, a sidewalk, and heavy false arch curtains * * *. This heavy concrete structure was carried more than half a mile down stream before the force of the flood diminished sufficiently to permit it to settle on the river bar.
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> A party of visitors were eating lunch on the parking area at the west end of the bridge when they heard the roar and saw the wall of water, mud, and rock moving toward them. Before they could start their automobile and escape the rushing water had covered the parking area and almost washed the car away. Three of the party were thoroughly wet to their knees and

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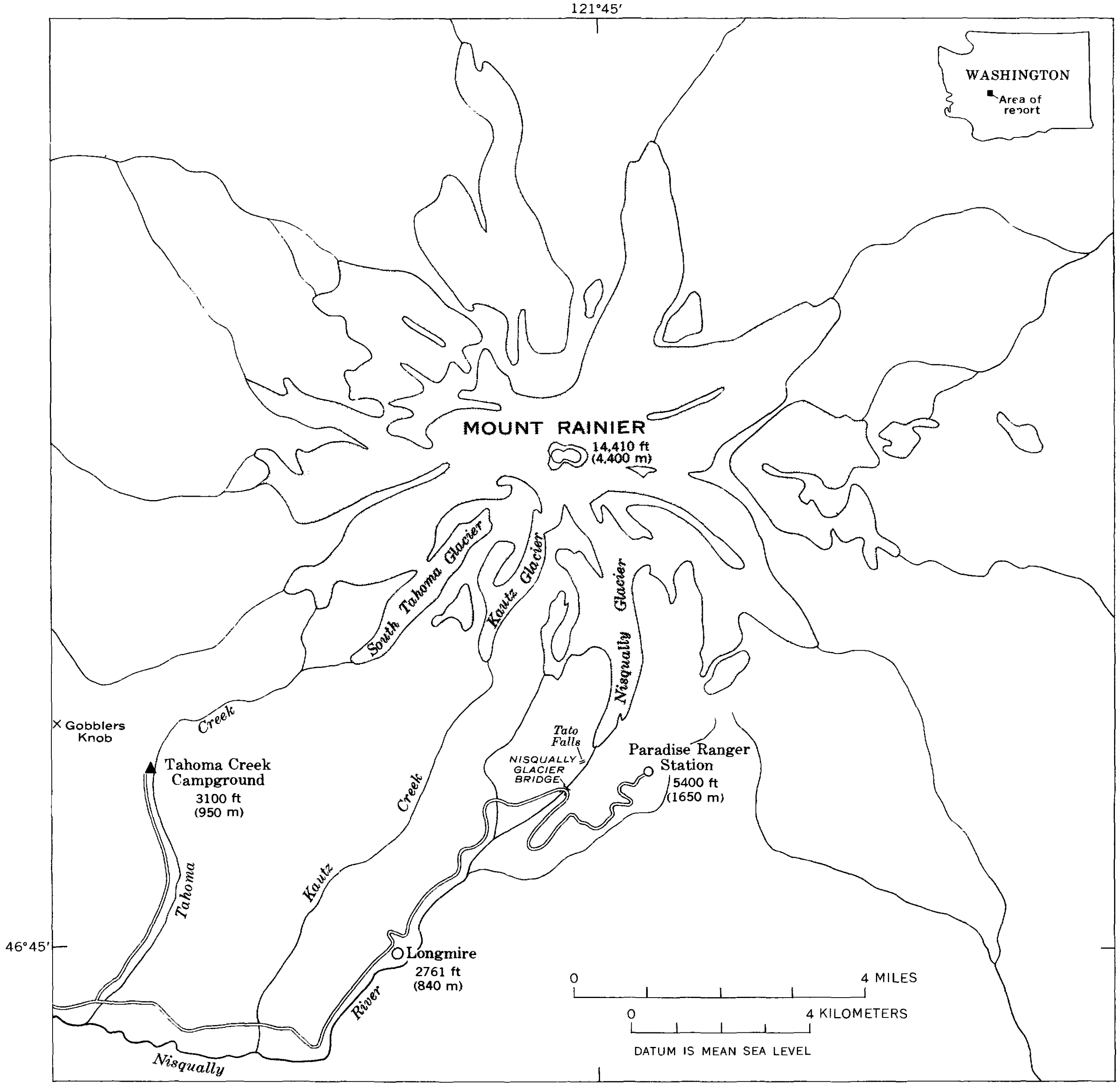

FIGURE 1.—Sketch map of Mount Rainier, Wash., showing the glaciers where outburst floods have been observed.

splashed with mud by the rushing torrent. Engineers Polk and Evanston of the Bureau of Public Roads were eye witnesses to the catastrophe. They saw the moving mass of water and rock coming over the end of the glacier and * * * described the material as similar to a huge mixture of concrete except that it was darker in color. They stated that the force was so great that immense boulders were thrown from ten to thirty feet into the air as the mass moved forward.

Three days after the flood, the lower part of Nisqually Glacier was inspected by Llewellyn Evans (Superintendent of Light, City of Tacoma Department of Public Utilities). In an unpublished report, Evans stated that the ice was swept clean along the west edge of the glacier and over the entire ice front. The flood also washed away debris for some 500 feet below the terminus, exposing ice on the valley floor.

Evans examined the west lateral moraine to a point beyond the first bend in the glacier. He came upon a break in the moraine and concluded that water had likely gathered in the open formation of the moraine and built up enough head to cause a sudden break, which caused the flood by the outpouring of all the water stored in the loose material. This conclusion is probably incorrect. Even though recent moraines appear to be loosely compacted, they do not contain sufficient openings to store a large volume of water—certainly, not enough to result in a flood like that of October 1932. It is more likely that the large slide was a result rather than the direct cause of the 1932 flood. Such slides commonly occur during and soon after outburst floods because of excessive erosion near the base of unstable slopes on lateral moraines.

Another outburst flood occurred at Nisqually Glacier on October 24, 1934, after several days of continuous downpour. The following brief account appears in a monthly report of Park Superintendent O. A. Tomlinson

> On October 24 and 25 a series of floods having their source on the Nisqually Glacier destroyed the approaches and superstructure, and badly damaged the arch of Nisqually Glacier bridge. There were four distinct floods or surges caused by slides damming a valley or ravine between the lateral moraine and the glacier and impounding the water from melting snow and heavy rains. The first surge occurred during the night of October 24, carrying down a stream [of] huge boulders, mud, and other debris from the moraine. Thousands of tons of rock and debris crushed the railing and filled the comfort stations in the abutments. The second and subsequent surges, which occurred during the 25th, completely plugged the bridge and piled rock and debris fifteen feet deep on top of the arch. Approach roads on both sides of the bridge were washed out and some minor damage occurred to trucks and other equipment that were being used by repair crews trying to save the bridge.

As in 1932, the outburst flood of October 1934 was thought to be caused by slides on the lateral moraine of Nisqually Glacier. Only one surge was noted in 1932, whereas in 1934 there were three or four distinct surges, which caused only moderate damage to the bridge.

C. E. Erdmann and Arthur Johnson, U.S. Geological Survey (written commun., 1953), made the following observations based on records of precipitation at Paradise Ranger Station and records of Nisqually River discharge near Alder (drainage area, 249 sq mi, or 645 km^2) during the 1932 and 1934 floods:

> In 1932 there was no recorded rainfall at Paradise from September 25 to October 9. During October 10–14, rainfall totaled 8.70 inches and the discharge of the Nisqually River near Alder during this period rose from 297 to 761 second-feet. In 1934, during the period October 1–19, rainfall was recorded on seven days totalling 1.51 inches and during the period October 20–25, it totaled 9.92 inches. The discharge of the Nisqually River near Alder during this latter period rose from 682 to 12,000 second-feet. It is of interest to note that in 1934 with heavier rainfall the surges were less destructive than in 1932.

A new concrete bridge was constructed below Nisqually Glacier in 1936 (fig. 2). This was a massive concrete-arch structure with a clear span of 80 feet (24 m) and a width of 34 feet (10 m). In October 1947, at the time of the great Kautz Creek flood, the Nisqually Glacier bridge withstood a torrent of water that came from the glacier. The Nisqually River rose to flood stage on October 1, and a deep, V-shaped gorge was cut into the glacier by running water. The following day, the torrential rainfall reached its peak when 2.38 inches fell at Longmire and 5.89 inches at Paradise Ranger Station. A surge of high water damaged two trucks and a gasoline-powered shovel that had been working on the channel at the Nisqually Glacier bridge. The bulk of the flood water was undoubtedly

FIGURE 2.—Nisqually Glacier bridge before and after the flood of October 25, 1955. In the earlier view (above) the bridge is seen as it appeared soon after its construction in 1936. The terminus of Nisqually Glacier is visible in the background. After the 1955 flood all that remained of the bridge were the broken abutments and exposed reinforcing bars seen in the latter view (below). The large boulders on the far bank were left by the flood. Photographs by M. K. Potts, National Park Service.

storm runoff, but the peak flow may have been increased by a sudden release of water stored at the glacier.

Eight years later, on October 25, 1955, a spectacular jökulhlaup occurred at Nisqually Glacier. This is the best documented of any of the outburst floods on the Nisqually River, having been observed at an uncomfortably close range by Park Ranger Dwight L. Hamilton. Rain had begun falling at 4 a.m. on October 24, after 2 days of clear warm weather. At 4:30 p.m. on the 24th, the rainfall measured 1.72 inches (43.7 millimeters) at Paradise Ranger Station, and by 12:15 p.m. the following day an additional 3.79 inches (96.3 mm) had fallen. On the morning of October 25, Hamilton was watching the rising water at the Nisqually Glacier bridge while sitting in a panel truck that was parked about 90 feet (27 m) from the east bridge abutment. He later reported the following (written commun., 1955):

> * * * [by 9:30 a.m.] water had been thrown around the [west] end of the bridge, washing boulders up to about 2 feet in diameter across and down the road. Several blocks of ice weighing about 20–30 pounds were seen.
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> For a time it looked as if the water level was dropping * * *. [Then] I glanced upstream in time to see water headed for me and the truck * * *. By the time I began backing up the road, I was engulfed by water, the motor stopped, and visibility was cut to zero by the muddy water. The truck was bounced around quite violently and pushed back another 10 yards. When things quieted down I looked out to see the bridge was gone * * *.
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> The following 45 minutes or so of watching are hard to describe. After the initial surge of water which took out the bridge, the water level would drop to a point where you could see the remains of the bridge abutments, then another surge which appeared to be at least 15–20 feet higher than the river level immediately in front of it would appear * * * and the abutments would again be hidden from sight. These surges probably came five or six times while I watched, each approximately the same size. The astounding thing was the size of the boulders and blocks of ice that the water carried. I would estimate some of them to be larger than an auto. They did not roll or turn but rode the surface of the water as a boat, the same end always down stream and the same surface out of the water. Occasionally large chunks of ice would collide with a rock and crumble, small pieces being thrown high into the air. The speed at which the rocks and ice traveled is hard to estimate but in comparing their speed with that of a car going by I would say between 30 and 40 miles per hour.

The figure 2 photograph shows the twisted steel reinforcing rods and broken concrete—all that remained of the Nisqually Glacier bridge after the 1955 flood. The flood wave that destroyed the concrete bridge also swept away a log bridge 1.8 miles (2.9 km) downstream. (This was witnessed by a group of miners at 10:15 a.m.). Some damage was also done at Longmire, where the Nisqually River was reported to be at a high stage from 11 a.m. to about 2 p.m.

An interesting feature of the 1955 flood observed by Hamilton was the repeated surges "each approximately the same size" that followed the initial outburst for a period of about 45 minutes. These secondary surges have been observed following other outbursts, and apparently are a characteristic feature of this type of flood. They might have been caused by the repeated plugging and unplugging of channels within the glacier, or temporary damming of the river by a series of slides from the unstable moraine.

On November 7, 1955, Park Ranger Aubrey L. Haines made a reconnaissance along the river from the site of the Nisqually Glacier bridge up to an altitude of about 6,000 feet (1,800 m) on the Nisqually Glacier. He reported (written commun., 1955) that at places the floodwater had been over the trail where it was 40 to 50 feet (12 to 15 m) above the river bottom. Upstream from Tato Falls, the trail was completely washed away as were the year dates that had been painted on large rocks to mark positions of the glacier as early as 1922. The streambed was cut by a wash 30 to 40 feet (9 to 12 m) deep and about 100 feet (30 m) wide near the old glacier terminus. Above the old terminus a canyon had been carved in the mass of stagnant ice that had remained under glacial debris after the glacier retreated some years before. This dead ice had been melting slowly even after the glacier's active terminus began to advance in 1953. Haines described in detail the channels that were formed in the stagnant ice and advanced the opinion that they were not entirely the result of the cutting action of flood waters, but were formed largely by "hydrostatic pressure blowing the roof from an existing water channel, or subglacial stream."

Above the upper, or active, ice face, a large gully had been formed for half a mile (0.8 km) along the west side of the glacier. It appeared to Haines to have been created by the removal of both morainal debris and glacial ice. Above the gully, the ice surface had a glossy, washed look as if a large quantity of water had flowed over it.

Two days after Haines' inspection of the lower part of Nisqually Glacier he assisted in a survey of the river channel near the site of the Nisqually Glacier bridge and found the cross-sectional area of the flooded channel to be 5,120 sq ft (476 m^2). He estimated that a velocity of 18 miles per hour (8 m/sec) would have been required to transport a large boulder (960 cu ft, or 27 m^3) that was deposited on the roadway during the flood. Assuming an average stream velocity of 20 mph (8.9 m/sec), he concluded that the peak discharge was about 150,000 cubic feet per second (4,250 m^3/sec). The estimate seems high. On the basis of the channel slope and roughness at the bridge, an average velocity of 20 feet per second (6.1 m/sec) seems more likely. If a sediment concentration of 30 percent by volume is assumed, the estimated peak discharge of water would then be about 70,000 cfs (2,000 m^3/sec).

Since 1955, there have been no reports of any more outburst floods on the Nisqually River. Soon after the bridge was destroyed in 1955, it was replaced by a Bailey bridge that was used until the present span was completed in 1960. Compared with earlier bridges at the site the present structure is immense, having a clear height of 85 feet (26 m) above the river and a clear span of 300 feet (92 m) between the piers. With that much clearance the bridge is not so likely to be damaged by outburst floods. The river's discharge is now being recorded at a gaging station that was installed at the bridge on March 1, 1968.

Kautz Creek

According to Russell K. Grater, a former park naturalist at Mount Rainier, the destructive Kautz Creek flood of October 2, 1947, was one of the most spectacular events that has ever taken place in a National Park since the beginning of the Park Service. Grater, with a group of local residents, was watching the mudflow when it reached its final and climactic stage at the highway bridge 5.5 miles (8.8 km) below Kautz Glacier. In a written communication (1947) he described the scene as follows:

> A vast fan-shaped sea of rock and log debris was pouring down across the Nisqually Entrance Highway toward the Nisqually River. The force of the moving mass was terrific, with huge boulders being carried along like so much float material. One boulder was measured that reached approximately 13 feet in diameter. In many instances these boulders did not roll, but simply moved along buoyed up by the thick, cement-like material flowing across the region. Trees, even large ones with diameters in excess of three feet, were snapped off like sticks or else were uprooted. * * *. All of this activity was accompanied by a rumbling and earth shaking that was awesome in its magnitude.

After the flood, Grater inspected the Kautz Creek valley floor at the Kautz Glacier, where he saw the effects of the outburst near its source. His report continues:

> Evidence shows that approximately one mile in length of the Kautz Glacier was destroyed during the flood. Where the glacier once lay is now a deep canyon, ranging up to approximately 300 feet in depth and approximately 300 yards wide at the widest point. These figures are considered to be on the conservative side. Along the east side of the newly cut canyon is a large segment of the original glacier, now cut off and left stranded by itself. The segment is approximately 75 feet thick at the lower end of the ice mass. The canyon itself has been cut completely down to the original granite bedrock. * * *.
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> At the box canyon of the Kautz, where it is believed the major surges developed through a damming up of the narrow channel, the canyon has been cut approximatly 60 feet in depth. Here an entirely new channel has been cut, with the old stream bed of the Kautz left high on the west side of the canyon.

Damming the box canyon compounded the destructiveness of the flood, for great masses of mud and debris were swept downstream in repeated surges that destroyed a large area of forest, as well as the Kautz Creek bridge, and covered part of the highway. The volume of material removed by the flood was estimated by the Park Service to be about 50 million cubic yards (38×10^6 m^3).

Some idea may be had of the discharge of water during the flood if it is assumed that the mudflow contained, on the average, about 40 percent water by volume. By further assuming that all the mudflow occurred in a 24-hour period, the average daily discharge of water required to transport the debris can be estimated as about 10,000 cfs (280 m^3/sec). The peak discharge was undoubtedly several times greater than the daily rate of flow and, in addition, there was probably more water flowing at times than was required to transport the material that was removed.

The Kautz mudflow of 1947 was the compound result of an abnormally intense downpour of rain and the release of additional water that was stored within the Kautz Glacier. The outburst of large amounts of water, combined with tremendous volumes of glacial sediment and rock debris that became temporarily trapped in the narrow box canyon, resulted in the spectacular mudflow in the lower Kautz Creek basin.

Previous debris flows on Kautz Creek are evidenced by older deposits that are exposed in cut banks (Crandell and Mullineaux, 1967, p. 18). The earlier debris flows go back at least 3,000 years and it is not known whether any of them resulted from an outburst flood.

On August 23, 1961, a flood was observed at the Kautz Creek bridge that was clearly the result of a jökulhlaup. No significant amount of rain had fallen in the area during the month, and the average temperature in August was the highest recorded since 1914 at Longmire. Park Superintendent Preston P. Macy reported that on August 23 Kautz Creek began a rampage with very muddy water and heavy surges taking place about every 2 hours. Later surveys at the bridge showed that the streambed was cut 7–10 feet below its previous level. Two trail bridges were destroyed on Kautz Creek during the flood.

Tahoma Creek

On August 31, 1967, during an exceptionally warm and dry summer, an outburst flood was observed on Tahoma Creek. Prior to August 31 no rain had fallen in the area for about 2 months, and the fire hazard was so severe that the Tahoma Creek campground was closed to the public on August 30. The closure turned out to be a fortunate circumstance, for on the next day part of the campground, which is 3.5 miles (5.6 km) below South Tahoma Glacier, was swept over by a flood of water, mud, and debris.

Two days earlier, a short-lived outburst had destroyed a footbridge 1.2 miles (1.9 km) below the glacier, but the stream rose only about 1.5 feet (0.5 m) at the campground. On August 31, David Fluharty, fire control aid at the Gobblers Knob fire lookout about 5 miles (8 km) from South Tahoma Glacier, reported hearing a loud roaring noise coming from the Tahoma Creek valley at 8:40 p.m. He could see water flowing across the surface of the glacier, apparently breaking out at an altitude of about 7,500 feet (2,300 m). Between 9:00 and 9:30 p.m. James Erskine, a park ranger, found that the lower part of the campground was being buried by a slurry of mud and boulders. In the main stream, large boulders were being swept along by the torrent, and many smaller stones were being thrown into the air. Erskine noted that the mudflow had the appearance of fresh concrete, a resemblance that had been observed by others during outburst floods on Kautz Creek and Nisqually River. The rate of flow decreased rapidly downstream from the campground, and a later inspection by D. R. Crandell (U.S. Geological Survey) revealed that the deposits of mud and debris terminated within a mile (1.6 km) downstream. At the highway bridge 4.3 miles (6.9 km) below the campground, Park Service personnel observed that Tahoma Creek crested about 10:30 p.m. Later inspection of high-water marks by the writer revealed that the stage had risen only about a foot (0.3 m) at the bridge, and the peak discharge at that point was estimated to be about 100 cfs (3 m^3/sec).

On September 2, the writer inspected the upper reaches of Tahoma Creek and the lower part of South Tahoma Glacier. At the campground, where the channel slope averages about 10 percent, the cross-sectional area of the flooded channel was about 1,200 sq ft (110 m^2). An average velocity during the flood peak of 20 ft per sec (6 m/sec) seems reasonable, which would indicate a peak discharge of about 24,000 cfs (680 m^3/sec). If it is assumed that the flow contained about 50 percent water by volume, the maximum discharge of water must have been about 12,000 cfs (340 m^3/sec). It is remarkable that such a high discharge was almost entirely dissipated by channel storage and infiltration in a reach of only 4.3 miles (6.9 km) below the campground.

Between the campground and South Tahoma Glacier there was much evidence of a larger flood. Erosion of the channel was particularly evident in a half-mile (0.8 km) reach immediately below the glacier, where an estimated 50,000 cubic yards (38,000 m^3) of material was washed away by the flood of August 31. Below the active terminus, older, stagnant ice was found to be freshly exposed near the bottom of the channel.

The steep terminus of the glacier did not appear to have changed appreciably, on the basis of photographs taken in 1966. On September 2 the melt-water discharge was only about 30–40 cfs (0.8–1.1 m^3/sec), most of the flow being in a deeply eroded channel along the glacier's north margin. Aerial photographs revealed another large channel eroded by flood waters near the center of the glacier. As nearly as could be determined, the outburst of August 31 apparently reached the surface of the glacier at about the 7,500-foot (2,300 m) level, just as Fluharty reported. No firm evidence was found of geothermal activity that might have caused rapid melting.

Other outburst floods

Outburst floods are known to have occurred at other glaciers in the Pacific Northwest besides those at Mount Rainier. On August 15, 1963, a flood was observed below Chocolate Glacier (on Glacier Peak) by H. C. Chriswell, forest supervisor, while he was on a routine fire observation flight over the Mount Baker National Forest. In a written communication (1963), Chriswell reported:

> As we flew over Chocolate Creek a massive flow of what appeared to be muddy water had just started to move down Chocolate Creek from the snout of the Chocolate Glacier * * *. We circled for about ten minutes [and] in this time the flow moved the 2½ miles [to the Suiattle River]. The height of the frontal crest could have been anywhere between 20 and 40 feet high * * *. The flow was still continuing almost unabated from under the snout of the glacier when we left the area.
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> The only downstream damage occurred when the flood carried away our Skyline Trail bridge above the mouth of Miners Creek [about 5 miles downstream from Chocolate Creek]. A tremendous amount of channel change and silt deposition occurred in the upper Suiattle. Heavy silt deposit was noted along the Sauk River [below the Suiattle].

It should be noted that there was no precipitation near Glacier Peak on August 15, 1963, and the Chocolate Creek flood that day was obviously the result of a true jökulhlaup. Chriswell also reported that from the condition of the channel and deposition on the upper Suiattle River, these flows have occurred back through the years. According to Austin Post, U.S. Geological Survey (oral commun., 1968), the source of most of the large mudflows in the upper Suiattle River valley was at Chocolate Glacier, a part of which has rapidly disintegrated. The deeply eroded canyon of Chocolate Creek is seen in the photograph of figure 3, which was taken 2 months after the 1963 outburst flood.

Outburst floods have also been reported at glaciers on Mount Hood, Oreg., and according to James R.

FIGURE 3.—Aerial view from the eastern side of Glacier Peak on October 16, 1963. Chocolate Glacier is above canyon in center of picture. Photograph by Austin Post, U.S. Geological Survey.

Craine, U.S. Forest Service (written commun., 1961) they generally are experienced during the first warm fall rains of the year.

INTERPRETATION

It seems significant that glacier outburst floods in the Pacific Northwest have been observed only during late summer and fall, and do not coincide with "normal" floods downstream. Most floods on the larger rivers occur in the winter and are associated with periods of heavy rain and general flooding throughout western Washington. On the lower Nisqually River, for instance, the largest known floods were those of November 19C9, December 1917, December 1933, and November 1959. In contrast, jökulhlaups may occur at times when there is no rain at all.

During the floods that are described in this article, the peak flows were greater than might be expected from direct storm runoff. The magnitude and frequency of many floods resulting from storms in the Pacific Northwest have been analyzed by Bodhaine and Thomas (1964), and their analysis has been used to estimate the size of floods that could be expected to occur in the upper Nisqually River basin. In the following tabulation, estimates are given for peak flows expected at the three sites in the Nisqually basin where outburst floods are described:

	Drainage area		Mean annual flood		50-year flood	
	(sq mi)	(km²)	(cfs)	(m³/sec)	(cfs)	(m³/sec)
Nisqually River at Nisqually Glacier bridge	6.2	16.1	440	12	1,000	28
Kautz Creek at highway	13.5	35.0	750	21	1,700	48
Tahoma Creek at campground	6.3	16.3	400	11	920	26

The expected peak discharges may be compared with estimated flows experienced during outburst floods. At Nisqually Glacier bridge, the Nisqually Glacier outburst of October 25, 1955, resulted in an estimated peak discharge (adjusted for sediment concentration) of about 70,000 cfs (2,000 m^3/sec). The Kautz Creek flood peak of October 2, 1947, was probably on the order of 50,000 cfs (1,400 m^3/sec), and the Tahoma Creek flood of August 31, 1967, was estimated to peak at about 12,000 cfs (340 m^3/sec). In each of these events, the peak flows were many times greater than the expected magnitude of a "50-year" flood.

Some of the floods at Mount Rainier were obviously affected by landslides which temporarily blocked stream channels and stored some of the flow. The volume of water ponded behind such slides is limited, however, by the steep slope of channels near the mountain. (The glacier surfaces are also steep, excluding the possibility of much water storage over the ice.) To estimate the possible effect of a landslide at Nisqually Glacier, a rough computation can be made on the basis of average channel dimensions where slides were reported to have occurred. If it is assumed that a slide 30 feet (9 m) high blocked a rectangular channel 100 feet (30 m) wide where the slope is 15 percent, the volume of impounded water would have been 300,000 cu ft. (90,000 m^3). This is small in comparison to estimated volumes of as much as 50 million cu ft (1.4×10^6 m^3) which were probably discharged during outburst floods at Nisqually Glacier. It seems evident, therefore, that flood waters were released not only from behind landslides but also from within the glacier.

If there were a practicable way of determining the volume of water in a glacier at any particular time, the potential size of a jökulhlaup presumably could be estimated. The likelihood of an outburst might also be indicated by measurements of water pressures within glaciers. High water pressures in some glaciers have been evidenced by measurements during exploratory drilling. An example described by Mathews (1964) is at the South Leduc Glacier of British Columbia where an exploratory tunnel was driven in 1957. The mine tunnel made contact with the base of the glacier about 2 km above the terminus, where the ice was 150 m thick. Records of water levels in the mine, indicating water pressure in the upper part of the glacier, showed periods of moderately steady conditions (with slight diurnal fluctuations) interrupted by irregular and catastrophic surges, particularly during periods of rapid snowmelt and heavy rains.

Haefeli (1957, p. 27–29) has suggested that seasonal variations in water pressure at the base of a glacier may be responsible for seasonal variations in the rate of the glacier's movement, and Weertman (1962) has offered a theory that catastrophic advances of some glaciers are made possible by a basal layer of water. The relation of water pressure and rates of ice movement is not yet understood, however, and further study will be needed before the significance of these factors to glacier outbursts can be clearly shown. Some field measurements suggest that the flow of Nisqually Glacier normally decreases (suggesting perhaps lower water pressure) during August to October, which is the period when jökulhlaups occur. This seems to contradict the theory that outbursts are a result of sudden increases in water pressure. Conceivably, this apparent contradiction might be explained if it could be shown that water pressure may suddenly increase at times when there is not a noticeable increase in ice flow. Perhaps an increase in pressure occurs when decreasing melt-water flow fails to keep the plumbing open in late summer.

Mudflows are often associated with outburst floods, particularly at Mount Rainier where great quantities of loose glacial debris are readily available to streams. Beverage and Culbertson (1964) proposed a terminological limit for a mudflow, restricting the term to a flow having a sediment concentration of at least 80 percent by weight. (If a specific gravity of 2.65 is assumed for individual sediment particles, such a flow would contain about 40 percent water by volume.) Floods having sediment concentrations of 40–80 percent by weight are classified by Beverage and Culbertson as being "hyperconcentrated." On the basis of the high stream velocities described by witnesses during outburst floods on the Nisqually River and Tahoma Creek it would appear that those floods consisted, for the most part, of hyperconcentrated flows. As flood waves move downstream they sometimes degenerate into a mudflow because of insufficient slope and tributary inflow to overcome the loss of water by infiltration.

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