GEOMORPHIC CHANGE CAUSED BY OUTBURST FLOODS AND DEBRIS FLOWS AT MOUNT RAINIER, WASHINGTON, WITH EMPHASIS ON TAHOMA CREEK VALLEY

By Joseph S. Walder and Carolyn L. Driedger

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CONVERSION FACTORS

Multdply metric units	By	To obtain inch-pound units
millimeter	0.039	inch
meter	3.28	foot
kilometer	0.62	mile
square kilometer	0.39	square mile
cubic meter	35.3	cubic foot
meter per second	3.28	foot per second
cubic meter per second	35.3	cubic foot per second

Temperature in degrees Fahrenheit (°F) as follows: $°F = 1.8 \times °C + 32$

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ABSTRACT

Debris flows have caused rapid geomorphic change in several glacierized drainages on Mount Rainier, Washington. Nearly all of these flows began as glacial outburst floods, then transformed to debris flows by incorporating large masses of sediment in channel reaches where streams have incised proglacial sediments and stagnant glacier ice. This stagnant ice is a relic of advanced glacier positions achieved during the mid-nineteenth century Little Ice Age maximum and the readvance of the 1960's and 1970's. Debris flows have been especially important agents of geomorphic change along Tahoma Creek, which drains South Tahoma Glacier. Debris flows in Tahoma Creek valley have transported downstream about 10^7 m^3 of sediment since 1967, causing substantial aggradation and damage to roads and facilities in Mount Rainier National Park. The average denudation rate in the upper part of the Tahoma Creek drainage basin in the same period has been extraordinarily high: more than 20 millimeters per year, a value exceeded only rarely in basins affected by debris flows. However, little or none of this sediment has yet passed out of the Tahoma Creek drainage basin.

Outburst floods from South Tahoma Glacier form by release of subglacially stored water. The volume of stored water discharged during a typical outburst flood would form a layer several tens of millimeters thick over the bed of the entire glacier, though it is more likely that large linked cavities account for most of the storage. Statistical analysis shows that outburst floods usually occur during periods of atypically hot or rainy weather in summer or early autumn, and that the probability of an outburst increases with temperature (a proxy measure of ablation rate) or rainfall rate. On the basis of these results, we suggest that outburst floods are triggered when rapid input of water to the glacier bed causes transient increase in water pressure, thereby destabilizing the linked-cavity system. The probabilistic nature of the relation between water-input rate and outburst-flood occurrence suggests that the connections between englacial conduits, basal cavities and main meltwater channels may vary temporally. The correlation between outburst floods and meteorological factors casts doubt on an earlier hypothesis that melting around geothermal vents triggers outburst floods from South Tahoma Glacier.

The likelihood that outburst floods from South Tahoma Glacier will trigger debris flows should decrease with time, as the deeply incised reach of Tahoma Creek widens by normal slope processes and stagnant ice decays. Drawing analogies to the geomorphic evolution of a reach of Tahoma Creek first incised by an outburst flood in 1967, we suggest the present period of debris-flow activity along Tahoma Creek will last about 25 years, that is, until about the year 2010. Comparison of geomorphic change at Tahoma Creek to that in two other glacierized alpine basins indicates that debris-rich stagnant ice can be an important source of sediment to debris flows as long as floods are frequent or channel slope is great.

INTRODUCTION

Mount Rainier, the highest volcano in the conterminous United States, is extensively covered by glaciers, several of which occasionally release glacial outburst floods. A glacial outburst flood, sometimes called by the Icelandic term "jökulhlaup," may be broadly defined as the sudden, rapid release of water from storage in a glacierized basin. Worldwide, most outburst floods are due to drainage of ice-dammed subaerial lakes; at Mount Rainier, however, no such lakes exist, and the source of water for outburst floods must be either subglacial or englacial (Driedger and Fountain, 1989).

Most outburst floods released by glaciers on Mount Rainier incorporate sediment and transform to debris flows as they move downstream. Debris flows are dense slurries of water and sediment that resemble wet concrete. The sediment concentration by volume in a debris flow is typically 65 percent or greater, as compared to a concentration typically less than 1 percent in a water flood (Pierson and Costa, 1987). The largest clasts in a debris flow tend to be concentrated at the surface and at the margins and snout, which are commonly steep. Debris flows have done notable damage within Mount Rainier National Park: the toll of destruction since the park's inception includes four highway bridges, sections of roadway, a campground, picnic area, and numerous trail bridges (Richardson, 1968; Driedger and Fountain, 1989).

This report includes descriptions of outburst floods and debris flows that occurred at Mount Rainier during the period 1985 to 1992, and of efforts to monitor and possibly predict these flows. We initially included in our study four glaciers--South Tahoma Glacier, Kautz Glacier, Nisqually Glacier, and Winthrop Glacier (fig. 1)--but later focused attention on the South Tahoma Glacier, which has spawned more outburst floods than the others combined, and which has been the only glacier of the four to produce an outburst flood since 1987.

To understand the relation between outburst floods from South Tahoma Glacier and debris flows downstream along Tahoma Creek, we have studied the history of geomorphic changes associated with retreat of South Tahoma Glacier. Ice near the glacier's mid-1970's terminus now appears to be totally detached from the active part of the glacier, and a second body of ice, near the early-1980's terminus, is nearly detached (fig. 2). Those debris-rich ice masses are no longer being nourished by influx of ice to replace losses by melting and erosion, and are wasting away in place. Since 1967, outburst floods from the glacier have caused rapid incision of stagnant ice and proglacial sediments. Glacially derived sediment has been "transported away at rates far in excess of 'normal' material supply by subaerial weathering processes...result[ing] in many fluvial deposits that represent temporary storage areas for material" (Church and Ryder, 1972, p. 3059). Most of this report is devoted to describing the history of incision, the processes supplying glacially derived sediment to Tahoma Creek, the consequences of rapid sediment transport primarily by debris flows, and possible future changes to South Tahoma Glacier and Tahoma Creek.

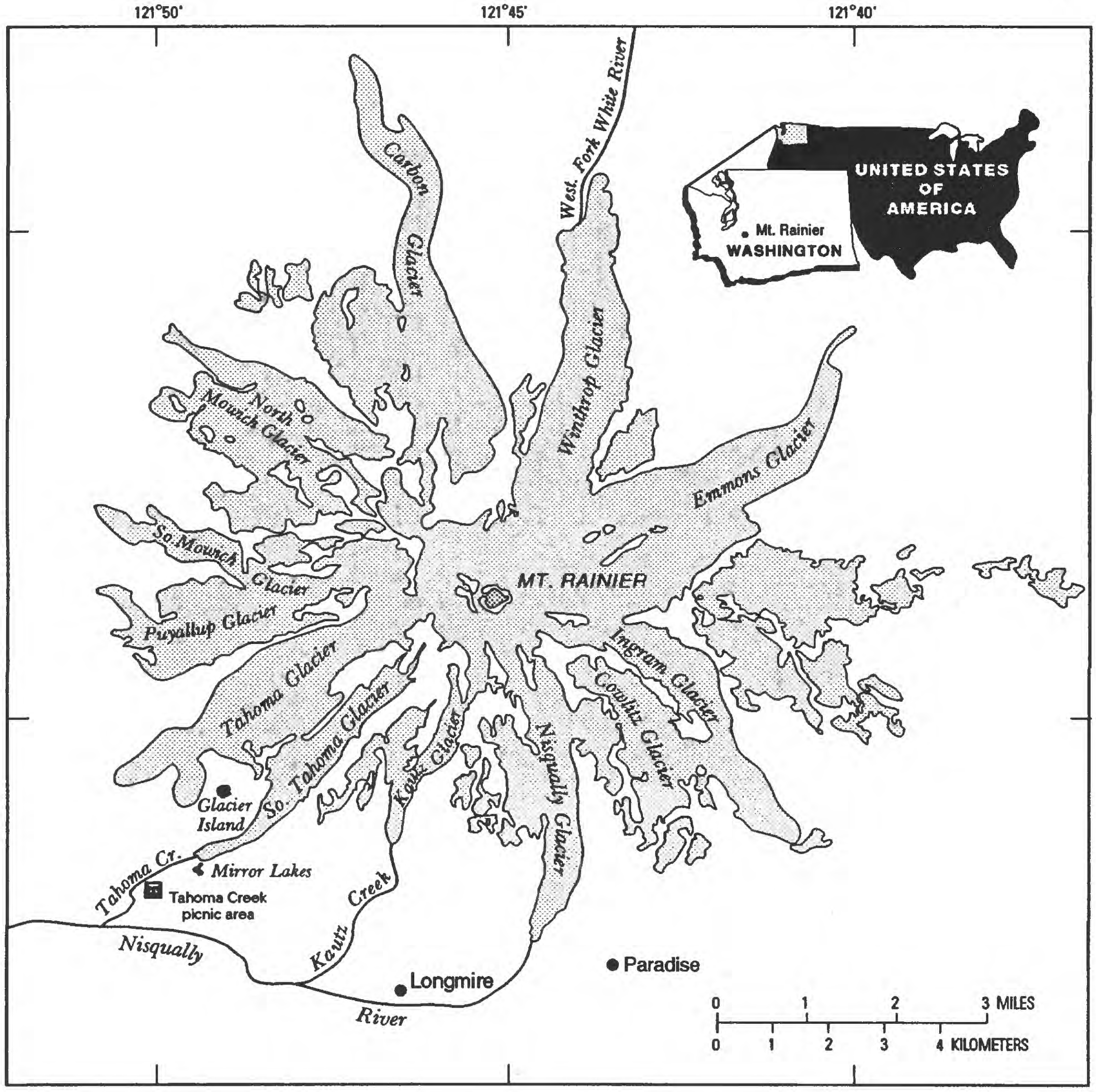


Figure 1.--Index map showing location of Mount Rainier and studied drainage basins. Glaciers are drawn to scale, but streams and cultural markers are shown only schematically.

Figure 2.--Oblique aerial photograph taken October 2, 1984, showing stagnant parts of South Tahoma Glacier and several locations mentioned in the text. Photographer unknown; photograph from USGS archives, Tacoma, Washington.

This study was undertaken by the USGS primarily in response to several incidents of damage to National Park facilities and roads caused by debris flows along Tahoma Creek, and the uncertainties posed by possible recurrence of such events. The National Park Service (NPS) provided partial funding for this study during the years 1988 to 1992.

The origin, behavior, sedimentology and hazards of a separate class of much larger debris flows at Mount Rainier--those usually associated with either volcanic activity or collapse of sectors of the volcanic edifice--are discussed by Crandell (1971) and Scott et al. (1992).

Purpose and scope

This report describes results of a study of geomorphic changes caused by glacial outburst floods and associated debris flows at Mount Rainier. Goals were to describe such geomorphic changes, determine the relation between outburst floods and debris flows, identify the cause of outburst floods and assess whether they could be predicted, and assess the probable longevity of debris-flow activity, especially in the Tahoma Creek drainage. The work was done during the period 1985 to 1992 and included (1) field study of debris-flow deposits and of temporal changes in channel morphology; (2) measurements of stream stage, turbidity and electrical conductivity in the hope of identifying possible outburst-flood precursors; (3) statistical analysis of the relation between meteorological variables and outburst floods or debris flows; (4) examination of historical aerial photographs and production of a new topographic map of the proglacial area to determine qualitatively and quantitatively the timing and amount of topographic change of the lower part of South Tahoma Glacier (including the stagnant-ice region) and the uppermost reach of Tahoma Creek during the period 1967 to 1992.

Description of field area

Glaciers covered by this study include Nisqually Glacier, Kautz Glacier, and South Tahoma Glacier, all on the southwest flank of Mount Rainier; and Winthrop Glacier, on the mountain's north flank. These glaciers are drained by (respectively) Nisqually River, Kautz Creek, Tahoma Creek, and West Fork White River (fig. 1). Kautz Creek and Tahoma Creek are themselves tributaries of the Nisqually River.

All four of the studied glaciers retreated and thinned substantially between about the mid-nineteenth century--the end of the Little Ice Age (Sigafoos and Hendricks, 1972)--and about 1960. Rapid retreat resulted in stagnant tongues of ice thickly covered by rock debris (fig. 3). Slight advance of these glaciers occurred between about 1960 and 1975 (summarized by Driedger (1986)), with advancing ice overriding older, stagnant ice. Rapid retreat and thinning resumed about 1975. All of the studied glaciers have a substantial amount of rock debris covering ice near their termini--even identifying the glacier termini can be a difficult task.

Figure 3.--Debris-covered terminus of the combined Tahoma Glacier/South Tahoma Glacier on August 21, 1913. Photograph 27790 by Asahel Curtis, courtesy of Washington State Historical Society.

Topography of the drainages of Nisqually Glacier and Kautz Glacier is shown in fig. 4. Topography of the Winthrop Glacier drainage is shown in fig. 5. These figures also show approximate glacier termini during the period of this study.

Because most of our work was focused on South Tahoma Glacier, we now describe that glacier and its drainage in more detail. South Tahoma Glacier is drained by Tahoma Creek, which is also fed by several tributaries, primarily one emanating from a lobe of Tahoma Glacier (fig. 6). Geomorphic evidence and historical photographs show that during the Little Ice Age (Grove, 1988) and until about the late 1930's, South Tahoma Glacier and Tahoma Glacier merged into a single stream of ice down-valley of the bedrock massif known as Glacier Island (figs. 3 and 7). Terminal-moraine positions (Sigafoos and Hendricks, 1972) show that at its Little Ice Age maximum, the glacier extended to a point slightly beyond the present location of the Wonderland Trail suspension bridge (fig. 7). By the late 1950's, the terminus of South Tahoma Glacier had retreated to the base of Glacier Island (fig. 7). The glacier then advanced over stagnant ice until the mid-1970's, since which time it has rapidly thinned and retreated.

The present upper zone of stagnant ice (fig. 7) comprises an ice body overlain by a veneer of rock, whereas the lower zone of stagnant ice is a complex layering of glacier ice and rock, with a debris cover at least 5 meters (m) thick. Sediment contained in debris flows at Tahoma Creek has been derived from the debris cover of the upper stagnant-ice zone, as well as (primarily) from slope failures within the lower stagnant-ice zone and adjacent lateral moraines (cf. Scott et al., 1992).

Tahoma Creek's primary source of flow is meltwater from South Tahoma Glacier. During the study period, typically two or three small streams emerged from the active glacier ice and flowed over the upper stagnant ice area (fig. 7) before merging into a single stream. Downstream of that point, beginning at about river km 12.5, the stream flows through a gorge, locally up to 40 m deep, incised into stagnant ice and sediments of glacial and laharic origin. The nature and history of that incision are described later and constitute critical factors in the geomorphic evolution of the drainage. The reach between about river km 9 and km 10.5 is a zone of conveyance, wherein the stream channel is commonly U-shaped owing to passage of many debris flows (fig. 8). The zone of debris-flow deposition lies below about river km 9. Boulder levees (fig. 9) are common in the depositional zone. Westside Road, which provides visitor access to popular trails on the southwest side of Mount Rainier, is located near Tahoma Creek in the depositional zone. A profile of the thalweg of Tahoma Creek is shown in fig. 10. Slope of the stream channel is as much as 0.2 m/m (12°) in the deeply incised zone and 0.1 m/m (6°) in the zone of boulder deposition.

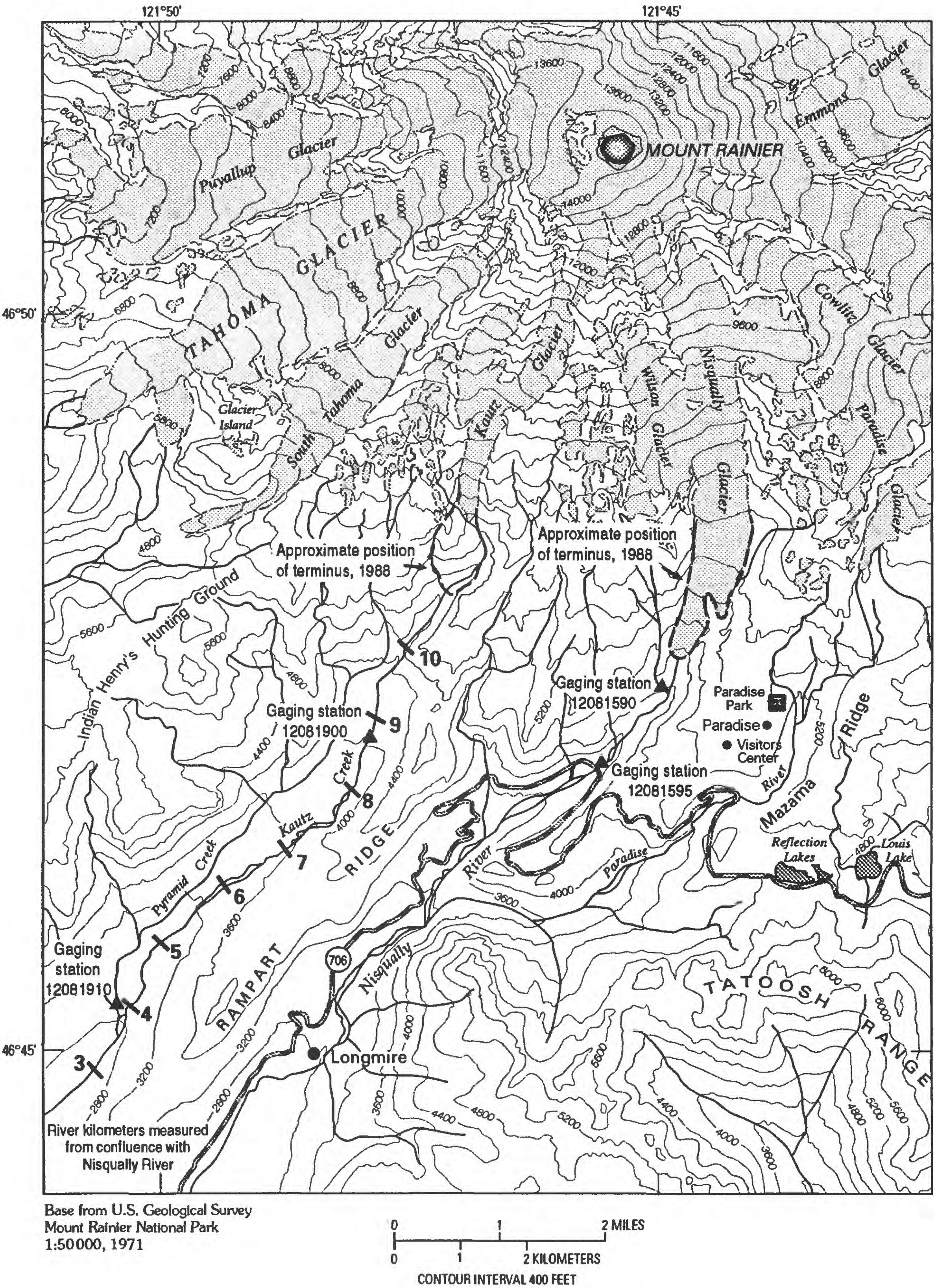


Figure 4.--Topographic map of Kautz Creek and Nisqually River drainages, and locations of gaging stations.

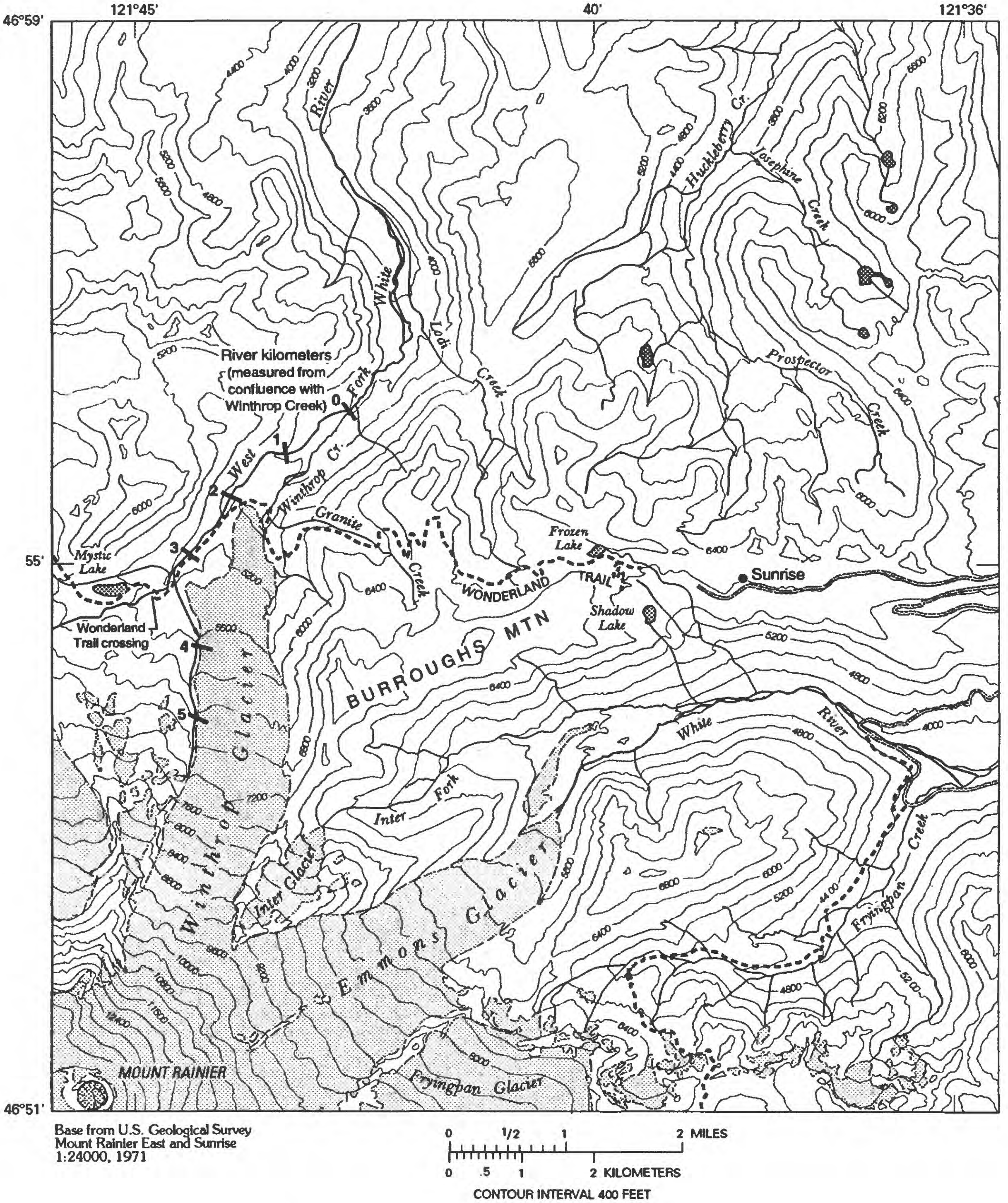


Figure 5.--Topographic map of West Fork White River drainage.

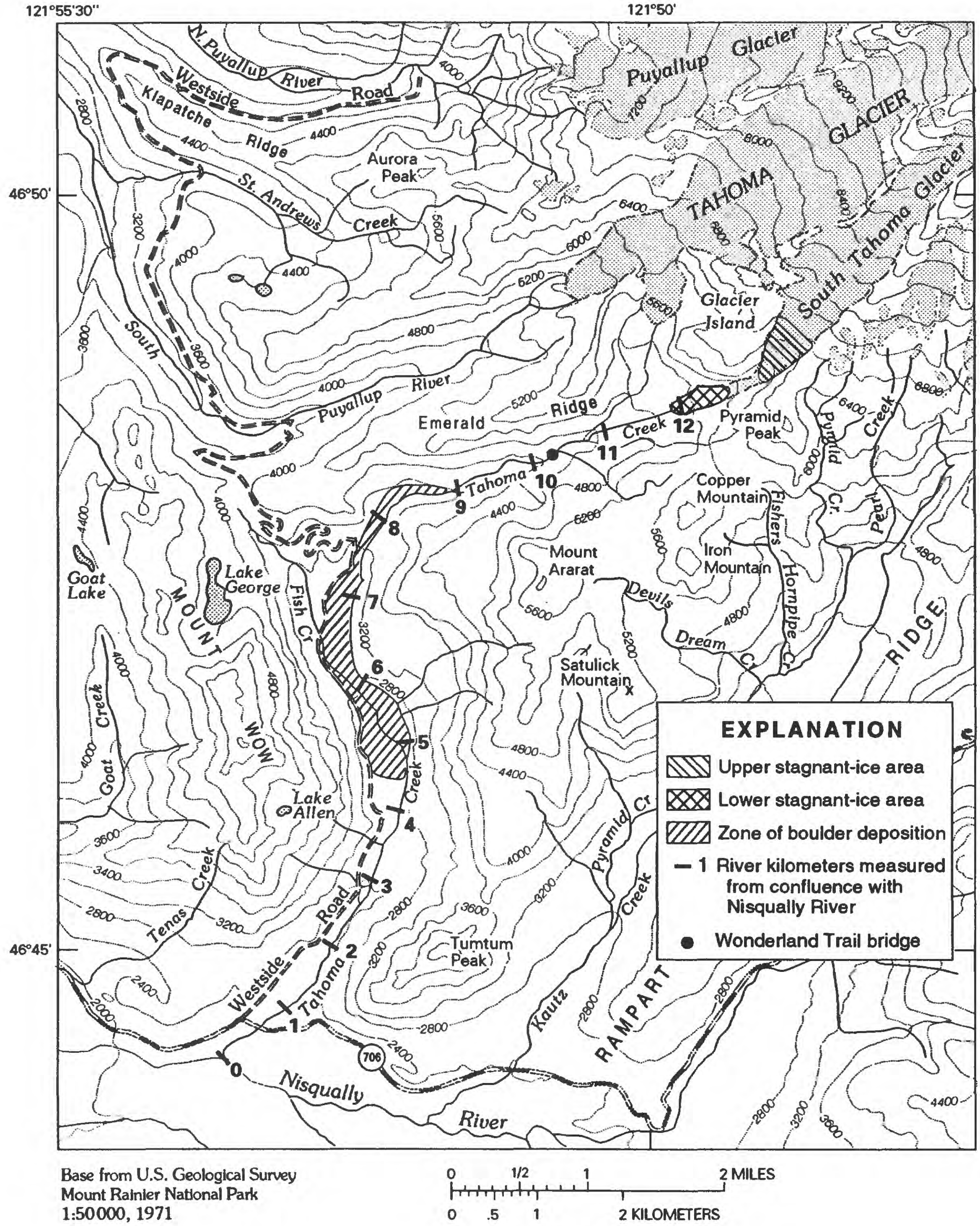


Figure 6.--Topographic map of the Tahoma Creek drainage. Locations mentioned in the text are indicated.

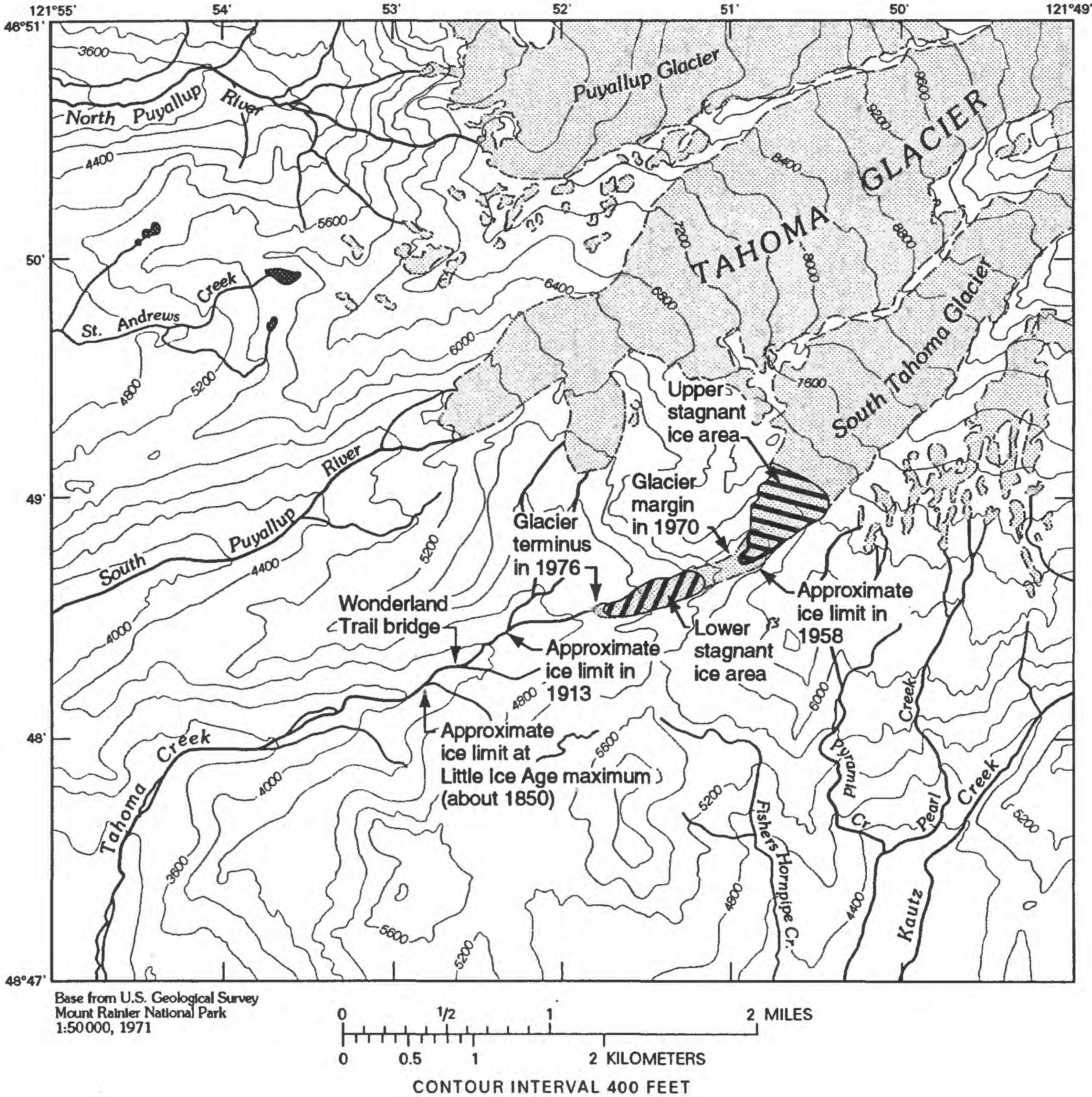


Figure 7.--Map of upper reach of Tahoma Creek and part of South Tahoma Glacier, including stagnant-ice zones and former positions of the glacier terminus.

Figure 8.--Tahoma Creek near river km 9.5, a reach of the stream that underwent little erosion or deposition during 1988 to 1992. The U-shaped cross section is characteristic of channels modified by passage of debris flows. Channel width is about 15 meters.

Figure 9.--Bouldery debris-flow deposits and levee along Tahoma Creek, near river km 7.5. Note people at lower right-hand corner for scale.

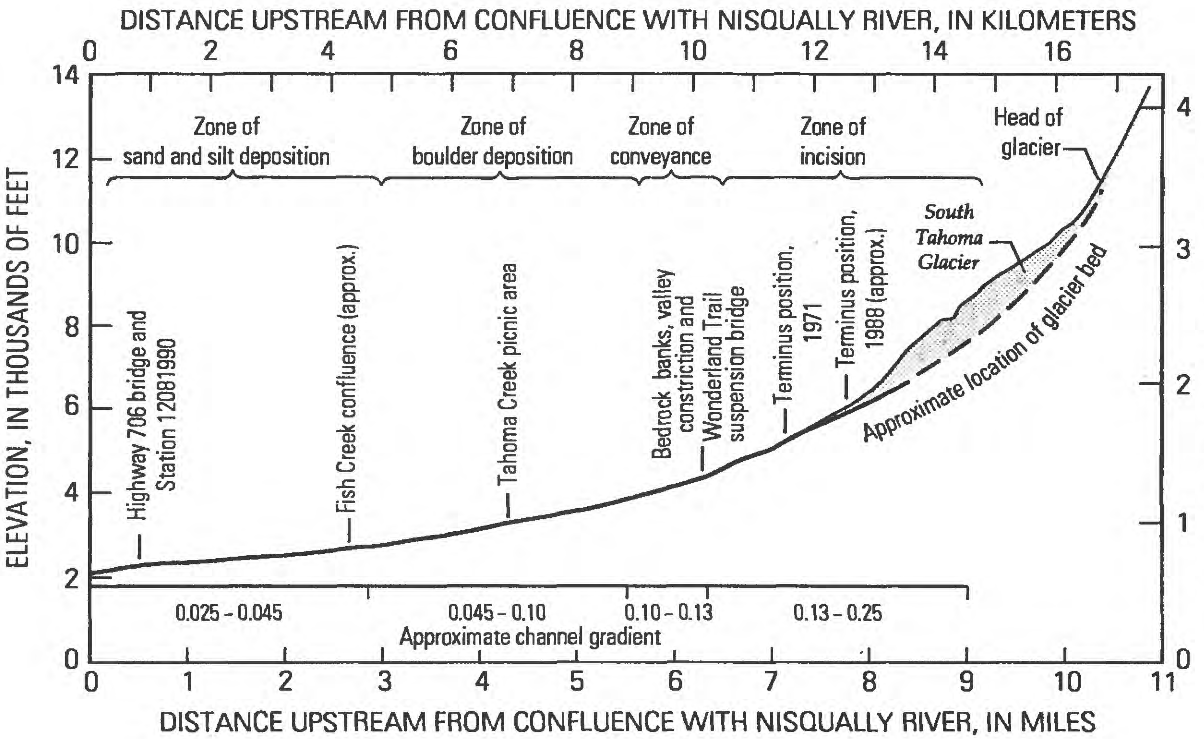


Figure 10.--Profile of the thalweg of Tahoma Creek.

Methods of investigation

Information about debris flows was gathered by interviewing witnesses, primarily NPS employees. Seismic records for stations operated by the University of Washington on or near Mount Rainier provided information about timing and duration of debris flows. We inspected deposits of debris flows whenever possible, usually within a few days of their occurrence. Wherever feasible, we tried to use morphological and sedimentological clues (Wigmosta, 1983) to infer values for peak discharge; errors in this method are probably large and are discussed in Appendix A.

Much of what we learned about temporal changes in channel morphology came from studying aerial photographs, especially sets of photographs taken in the autumns of 1988, 1990 and 1992. Aerial photographs taken in autumn of 1991 were used to produce a new topographic map of the Tahoma Creek drainage in the region of stagnant ice. The new map was compared with the USGS 1971 topographic base map to make quantitative estimates of channel incision and widening, as detailed below.

During 1987, instruments were installed along Kautz Creek, Tahoma Creek and Nisqually River to monitor stream stage, conductivity, turbidity, and local meteorological conditions. Data-collection sites are indicated on figs. 4 and 6. The purpose of this work was to look for possible hydrologic precursors to outburst floods or debris flows, with the hope of developing a capability for short-term debris-flow prediction. There were no debris flows in any of the monitored stream valleys during the period of data collection, and this part of the research effort was subsequently discontinued. The data that were collected are presented and discussed solely in Appendix B.

Two different statistical methods were applied to examining meteorological data (precipitation and temperature) collected at the Paradise Ranger Station. We used both commercial computer software (the SAS package) and computer programs that we wrote ourselves.

Acknowledgments

The National Park Service provided partial funding and administrative and logistical support for this study during the period 1988 to 1992. Discussions with M. Church of the University of British Columbia helped focus our thoughts and pointed out limits in interpretation of the data. C. Jonientz-Trisler and A. Qamar of the University of Washington helped interpret pertinent seismic records. Special thanks also to several USGS colleagues: A. Fountain helped install instruments at stream-gaging sites in 1987. M. Thorburn prepared the updated topographic map of the Tahoma Creek drainage, and L. Mastin gave invaluable assistance in analyzing the topographic data. E. Gilroy provided guidance on part of the statistical analysis. J. O'Connor's careful review of an earlier version of this manuscript was particularly helpful. R. Krimmel and D. Hirst provided numerous photographs from USGS archives in Tacoma, Washington.

RELATION BETWEEN OUTBURST FLOODS AND DEBRIS FLOWS

Outburst floods from alpine glaciers may or may not transform to debris flows; both cases are known at Mount Rainier and elsewhere. Even within a single drainage, the situation may change with time, as apparently has happened along the Nisqually River below Nisqually Glacier, as discussed later in this section. We therefore describe the relation between outburst floods and debris flows for the several studied drainage basins.

Tahoma Creek valley

Debris flows along Tahoma Creek have been recorded since at least 1967 (fig. 11). All have occurred during either summer or early autumn, as previously noted by Scott et al. (1992). Richardson (1968) and Crandell (1971) described some Tahoma Creek debris flows that occurred during the years 1967 to 1970, but for the period before 1986, the record is incomplete. Some sense of the uncertainty is conveyed by the words of Crandell (1971, p. 60), who remarked: "Floods not associated with rainfall also moved down the valley from time to time during the summer of 1968..." [our emphasis]. Debris flows during the years 1971 to 1985 are described only sketchily in records at Mount Rainier National Park (cited by Driedger and Fountain (1989)). It is therefore likely that the debris-flow count shown in fig. 11 is too low for the years 1967 to 1985. For the years 1986 to 1992, we believe the record of debris flows at Tahoma Creek is probably complete, largely owing to increased awareness among NPS staff. There were 15 debris flows from 1986 through 1992; they are briefly described in Appendix A. Detailed description of the sedimentology of deposits left by 2 of those flows is given by Scott and others (1992).

The NPS has been interested in identifying and understanding geomorphic change at Mount Rainier National Park, especially as it may relate to hydrologic hazards. At Mount Rainier National Park, the NPS has been especially interested in geomorphic change and hydrologic hazards along Tahoma Creek because Westside Road, the principal access route to trails and facilities on the southwest side of Mount Rainier, has been repeatedly damaged by debris flows along Tahoma Creek. Westside Road is particularly susceptible to debris-flow inundation because it follows the valley bottom near Tahoma Creek in a reach that has undergone aggradation at an average rate of about 0.5 meters per year (m/a) during the study period. The route of debris flows traversing this reach is unpredictable: commonly the channel occupied by the stream immediately prior to a debris flow becomes filled and the debris flow becomes diverted, sometimes onto the roadway (fig. 12). Debris flows since 1986 also have destroyed a picnic area and approximately 1 kilometer (km) of the former Tahoma Creek hiking trail.

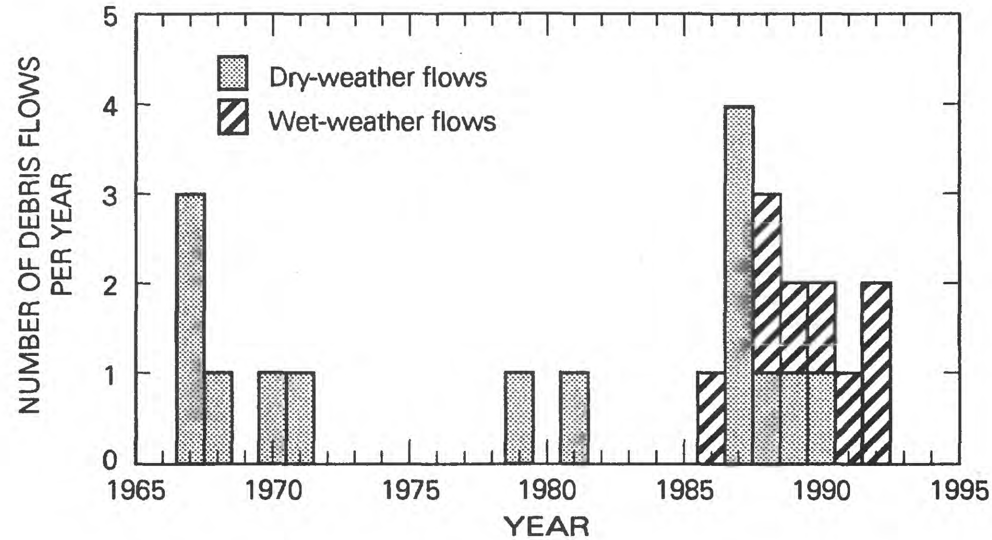


Figure 1.--Frequency of debris flows at Tahoma Creek.

Previous workers (Richardson, 1968; Driedger and Fountain, 1989) have argued that debris flows in the Tahoma Creek valley and in other glacierized drainages on Mount Rainier invariably have their origin in glacial outburst floods. Direct evidence of outburst floods, at least from South Tahoma Glacier, is actually rather meager--only one has ever been witnesses (by an NPS employee, according to Crandell (1971, p. 58)). There is also circumstantial evidence for outburst floods:

(1) On August 31, 1967 (Crandell, 1971), and again on October 26, 1986 and June 29, 1987 (Scott et al., 1992), water apparently emanated from the glacier at the base of an ice fall and eroded supraglacial channels (fig. 13). Scott et al. (1992) noted that deposits of debris flows triggered by the latter two floods contained abundant ice clasts.

(2) On August 4, 1990, geophones on Glacier Island and near the stream bank at about km 9 detected periods of high-frequency ground-shaking, of the sort known to be associated with water floods and debris flows (R. LaHusen, personal communication, 1993). Peaks in amplitude of shaking at Glacier Island preceded those at the downstream geophone by several minutes, as would be expected for a "flood" wave moving downstream. The stream bank geophone was nearly buried by debris-flow deposits.

Other evidence for occurrence of outburst floods is less direct and requires considerations of stream hydrology, to which we now turn.

Figure 12.--Debris-flow deposits of September 8, 1992 on Westside Road, near confluence of Fish Creek with Tahoma Creek (river km 5.0). The culvert diameter is about 1.5 meters.

Figure 13.--Front of South Tahoma Glacier, including upper stagnant-ice area, following outburst flood of June 29, 1987. Dark areas indicated by arrow are zones of ice collapse during the outburst flood. Photograph by K.M. Scott, USGS.

Dry-weather debris flows

Of the 23 known debris flows along Tahoma Creek since 1967, 15 occurred during periods of dry weather (fig. 11). The water discharge of those 15 flows was much greater than typical stream flow in Tahoma Creek, so it is tempting to hypothesize, as did Scott et al. (1992), that their water came primarily from outburst floods. This hypothesis is supported by considering the one debris flow for which we have an approximate hydrograph: the flow of July 26, 1988. C.H. Swift of the U.S. Geological Survey (written communication, 1988) observed the flow at about river km 9.1, in the zone of conveyance, and estimated the hydrograph and the relative fractions of water and sediment (fig. 14). Swift calculated that the peak water discharge was about 190 cubic meters per second (m^3/s) and that a total water volume of approximately 3×10^5 m^3 passed before discharge returned to ambient after about 80 minutes. The average water discharge during the debris flow was therefore about 55 m^3/s. For comparison, we measured discharge of about 3 to 4 m^3/s on a hot summer day in 1989, using the salt-dilution method (Kilpatrick and Cobb, 1984). A source of water other than normal stream flow therefore must have been involved in the debris flow. Three potential sources are (1) stream flow impounded upstream by a slope failure and then released catastrophically; (2) pore water held within stream bank sediments that slumped and thence moved downstream as a debris flow; or (3) an outburst flood.

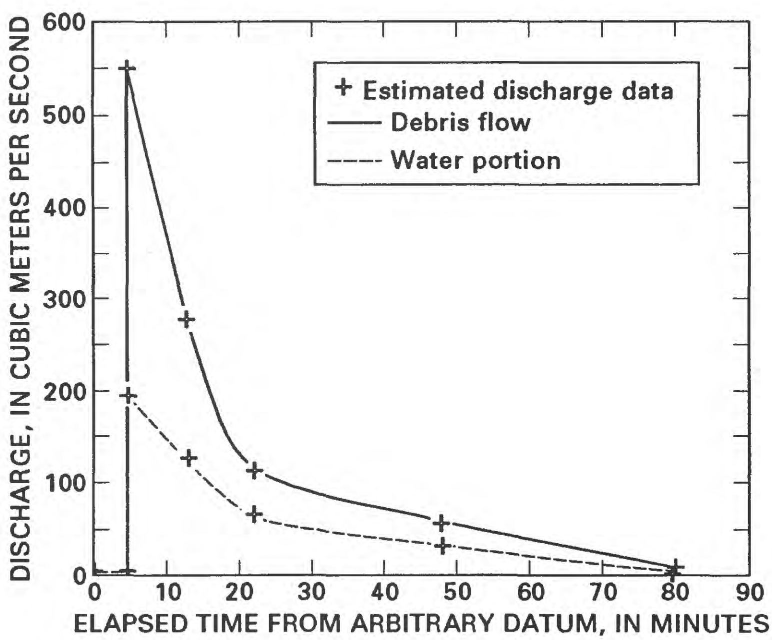


Figure 14.--Hydrograph of debris flow of July 26, 1988 at about river km 9.1, Tahoma Creek, as estimated by observer C.H. Swift, USGS. The total discharge of water plus sediment, as well as discharge of water only, are indicated separately.

Damming of Tahoma Creek by slope failures has never been reported, nor have we seen geomorphic evidence of damming. The estimated water volume within the debris flow of July 26, 1988 was approximately equal to the total normal flow of Tahoma Creek for an entire day, but because Tahoma Creek's flow was normal for several hours prior to the time of the debris flow (C.H. Swift, written communication, 1988), we are sure that no damming occurred on that day. Furthermore, a plausibly sized dam in the deeply incised reach of Tahoma Creek (channel gradient about 0.15), with a height of 10 m and a width of 25 m, would impound a water volume of only about 8300 m^3--about 2.5 percent of the water volume of the July 26, 1988 debris flow, which was typical, in terms of effects and extent of deposits, of debris flows since 1988. We conclude debris flows along Tahoma Creek cannot be explained by drainage of impounded water.

Saturated morainal sediment slumping into Tahoma Creek would have approximately the water content required to mobilize into a debris flow. During summer, however, sediments in the source area--the lower stagnant-ice area and adjacent moraines--are probably on average far from saturated. Field observations during extended rainless periods, such as the summer of 1988, show that those sediments are saturated only locally owing to melting of buried glacier ice or percolation of groundwater.

We therefore conclude that most of the water for the July 26, 1988 event must have been stored within or beneath South Tahoma Glacier. We further suggest that all debris flows noted by NPS personnel along Tahoma Creek during periods of sunny, dry weather have originated as outburst floods from South Tahoma Glacier. We have seen small (probably $< 10^3$ m^3) debris flows initiate as flowslides from the sediment veneer of the upper stagnant-ice area, but they moved at most a few hundred meters, never reaching areas frequented by NPS personnel and visitors.

Wet-weather debris flows

There is clear evidence that the October 26, 1986 debris flow described by Scott et al. (1992), and mentioned above, was triggered by release of water from South Tahoma Glacier. For other wet-weather debris flows, the possible link with outburst floods is less direct. One of those flows--the one of October 16, 1988--might have begun as a flowslide independently of an outburst flood. This debris flow occurred during one of the rainiest periods on record since 1986 (90 mm rainfall at the nearby Paradise Ranger Station on October, after a total of 85 mm on the two proceeding days--data from National Oceanic and Atmospheric Administration, 1986-1992). The source area for the sediment in this debris flow was a Little Ice Age lateral moraine (figs. 15 and 16). The geometry of the failure scar, which represents a sediment volume of about 10^5 m^3, is inconsistent with an origin of this feature as a rotational slump, and strongly suggests that the sediment had flowed in a liquefied state before even reaching the stream. It is nonetheless intriguing that comparison of figs. 15 and 16 shows that noticeable incision and stream avulsion occurred upstream of the October 16 failure scar between September 28 and October 28. These changes might have been caused by an outburst flood, but we cannot be certain.

The scar of the October 16, 1988 slope failure (fig. 16) has subsequently been modified by erosion--its condition in October 1990 is evident in fig. 17--but even in 1992 was notably different in shape from any other failure scar along Tahoma Creek. This supports the hypothesis that other debris flows at Tahoma Creek have not involved flowslides. Moreover, there is evidence that on one occasion, a sizable mass of sediment slumped into the gorge during a period of heavy rainfall, but did not mobilize into a debris flow. An aerial photograph taken October 11, 1990 (fig. 17), eight days after a debris flow had occurred, shows in the bottom of the gorge a slump block (volume probably about 10^4 m^3) derived from the adjacent slope at about river km 11. We confirmed this interpretation by comparing the 1990 photograph with a 1988 photograph of the same area. Tahoma Creek was apparently diverted by emplacement of this slump block in the bottom of the gorge. It is improbable that this block could have been emplaced in the bottom of the gorge prior to October 3, 1990, but been left unscathed by the debris flow on that date. If such is the case, the block must have been emplaced between October 3, 1990 and October 11, 1990. Meteorological records from Paradise (National Oceanic and Atmospheric Adminstration, 1986-1992) show that 7.8 cm of rain fell on October 4, 1990, and another 5.2 cm by October 11, so the block's water content must have been relatively high. Close examination of fig. 17 reveals, however, that the block did not deform viscously. Stratigraphic markers within the block are largely intact, in contrast to what would be expected if the block had begun to move as a debris flow.

Finally, we consider whether storm runoff alone could be sufficient to mobilize streambed sediments or trigger slope failures and thereby transform to debris flows. Hydrologic considerations do not support this idea. In addition to the 2 wet-weather flows already mentioned, there have been 6 others: 1 during each of the years 1988 through 1991, and 2 in 1992. These 6 flows, in their effects and the extent of their deposits, were roughly comparable to the July 26, 1988 dry-weather flow, for which we have an approximate hydrograph, so as an admittedly crude estimate, we assume that the peak water discharge Q_p of each of the 6 flows was about 200 m^3/s. In comparison, Richardson (1968), on the basis of regional flood-frequency relations suggested by Bodhaine and Thomas (1964), estimated Q_p = 11 m^3/s for the mean annual flood of meteorological origin in Tahoma Creek, and Q_p = 26 m^3/s for a flood with a 2 percent annual exceedence probability (the so-called 50-year flood). We therefore conclude that these 6 debris flows probably began as glacial outburst floods. Thus with a single possible exception--the October 16, 1988 event--we believe all recorded debris flows along Tahoma Creek were triggered by glacial outburst floods, probably similar to the "sudden break" outburst floods described by Haeberli (1983).

Figure 15.--Vertical aerial photograph taken September 28, 1988 of lower stagnant-ice area along Tahoma Creek. Arrow indicates position of subsequent large slope failure. Upstream is towards the top. Scale is approximate. Photograph by Washington State Department of Transportation.

Figure 16.--Vertical aerial photograph taken October 28, 1988 of lower stagnant-ice area along Tahoma Creek, showing scar of slope failure associated with the October 16, 1988 debris flow. Upstream is towards the top. Scale is approximate. Compare to Figure 15. Photograph by Washington State Department of Transportation.

Figure 17.--Vertical aerial photograph taken October 11, 1990. Arrow indicates slump block in bottom of Tahoma Creek gorge. The slump was probably emplaced after the debris flow of October 3, 1990. Upstream is towards the top. Scale is approximate. Photograph by Washington State Department of Transportation.

Nisqually River, Kautz Creek and West Fork White River

The oldest recorded glacial outburst floods and associated debris flows at Mount Rainier occurred in drainages other than that of Tahoma Creek, and have been described by Richardson (1968) and Driedger and Fountain (1989). During the study period, four floods or debris flows were detected in the valleys downstream of Nisqually Glacier, Kautz Glacier and Winthrop Glacier. Characteristics of those flows are summarized in Appendix A. The 1987 flood in the Nisqually River, which was witnessed by C.L. Driedger, was caused by a sudden release of water from Nisqually Glacier. Flood waters poured from a crevasse near the base of an ice fall and entrained superglacial sediment near the terminus, but did not transform to a debris flow--in which regard it was like the outburst floods from Nisqually Glacier in 1968, 1970, and 1972 (K.M. Scott, U.S. Geological Survey, written communication, 1993). The flood waters in 1987 spilled off the glacier, but caused little morphological change downstream to the bed of Nisqually River.

Debris flows that moved down Kautz Creek and West Fork White River during the years 1985 to 1987 occurred when the weather was hot and dry. As argued above in regards to the Tahoma Creek debris flows, the most plausible source of water for these flows was outburst floods. These debris flows left bouldery levees and deposits locally up to about 2 m thick, and destroyed small bridges over the Wonderland Trail. Sediment for these debris flows likely came from stagnant debris-rich ice.

RECENT GEOMORPHIC CHANGE IN TAHOMA CREEK VALLEY

To predict, for purposes of hazards assessment, possible styles and rates of future geomorphic changes in the Tahoma Creek drainage, we studied recent geomorphic changes along Tahoma Creek and related them to episodes of outburst floods. It is convenient to discuss separately the geomorphic evolution of the erosional and depositional zones. There was no corresponding archival photographic record for the depositional zone of Tahoma Creek, so we report only on recent geomorphic change in that zone.

Erosional zone

Geomorphic evolution of the erosional zone of Tahoma Creek was particularly well illustrated by a large, archival collection of photographs, primarily aerial photographs taken since 1958. In the narrative that follows, we make extensive reference to a number of those photographs, as well as to our field observations since 1985.

On August 16, 1967, the main branch of Tahoma Creek issued from stagnant ice in front of the advancing South Tahoma Glacier and flowed over a relatively low-relief outwash plain (fig. 18). The confluence of the main branch with the tributary issuing from Tahoma Glacier coincided with the upstream end of a narrow, bedrock-walled reach. About 100 m downstream of this confluence, the Wonderland Trail crossed Tahoma Creek via a log bridge about 1 m above the streambed.

Three floods or debris flows apparently originating in outburst floods from South Tahoma Glacier occurred between August 29, 1967 and September 15, 1967. The first of these debris flows destroyed the log bridge. An aerial photograph taken September 18, 1967 (fig. 19) shows incision of the main branch of Tahoma Creek in the vicinity and upstream of the confluence with the Tahoma Glacier tributary. This incision marked the start of major, rapid geomorphic changes in the Tahoma Creek valley that continue to this date.

Mike Carney, presently trail-crew foreman for Mount Rainier National Park, has been involved with construction of bridges over Tahoma Creek since destruction of the log bridge in August 1967. According to Carney (oral communication of August 18, 1992), Tahoma Creek incised its bed in the vicinity of the bridge crossing by about 5 to 7 m between the events of August and September, 1967 and the debris flow of August 10, 1971. An uncertain number of outburst floods/debris flows had occurred in the interim (Crandell, 1971, p. 60).

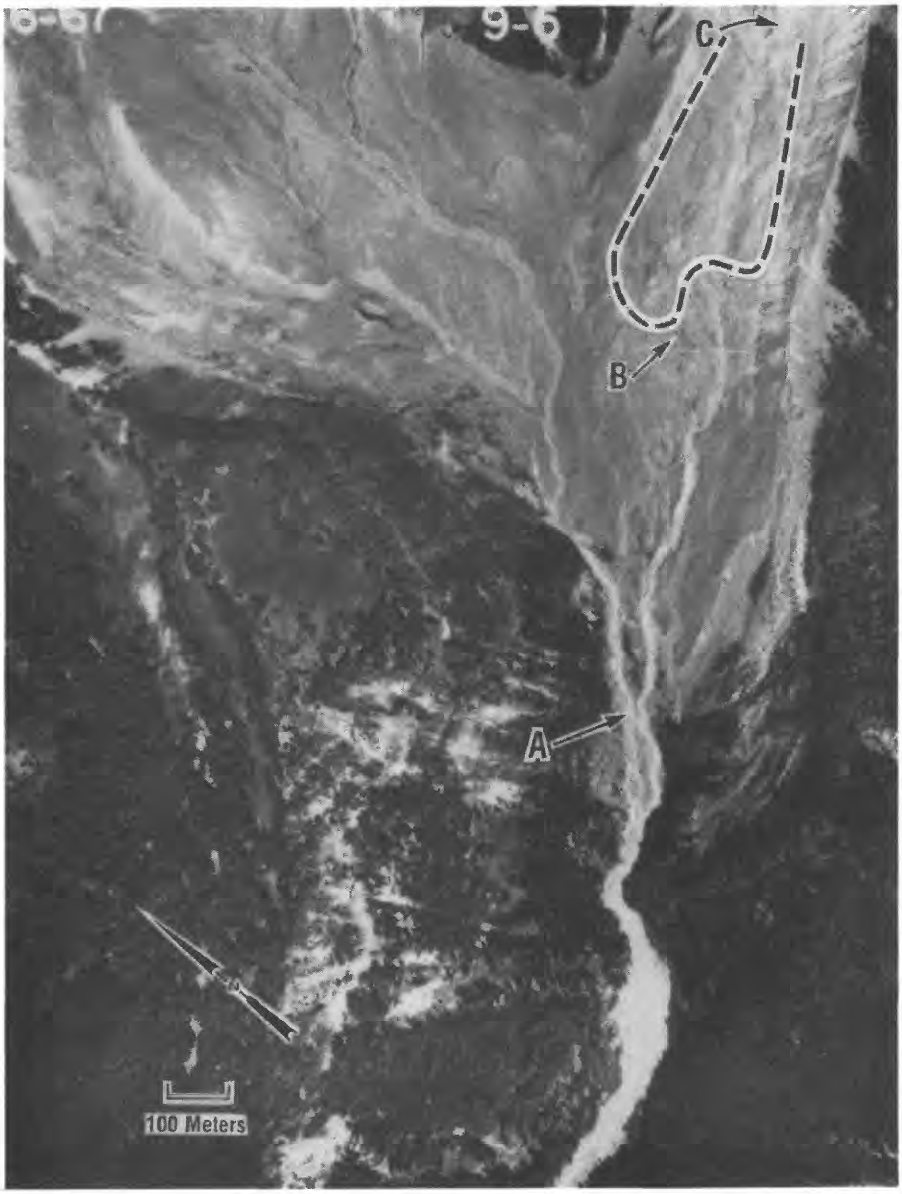


Figure 18.--Vertical aerial photograph taken August 16, 1967 showing upper reach of Tahoma Creek prior to onset of outburst-flood activity from South Tahoma Glacier. Marked points are (A) confluence with tributary stream from Tahoma Glacier, (B) stream issuing from stagnant ice, and (C) advancing terminus of South Tahoma Glacier. Dashed line delineates stagnant ice. Upstream is towards the top. Scale is approximate. Photographer unknown; photograph from USGS archives, Tacoma, Washington.

Figure 19.--Vertical aerial photograph taken September 18, 1967 showing upper reach of Tahoma Creek and terminus region of South Tahoma Glacier. Arrow indicates area of incision along Tahoma Creek upstream of confluence with tributary from Tahoma Glacier. Dashed line delineates stagnant ice. Upstream is towards the top. Scale is approximate. Photographer unknown; photograph from USGS archives, Tacoma, Washington.

An oblique aerial photograph taken October 12, 1972 (fig. 20) clearly shows incision by Tahoma Creek in the five years following the 1967 events. Owing to about 10 m of local incision by the main branch of Tahoma Creek, the tributary stream from Tahoma Glacier joined the main stem of Tahoma Creek (as it does today) through a steep, bouldery chute. Upstream of this confluence, the main stream flowed through a narrow gorge instead of over the broad outwash plain, as it had prior to the 1967 outburst flood. The point 'B' in fig. 20 marks where a tributary stream that drained from stagnant ice joined the main stream in 1967 (compare to fig. 18). The linear depression 'C' coincides with the path of that tributary. Aerial photographs taken in 1969 and 1970 (not shown here) appear to show water flowing along that stream course, but by the time of the 1972 photograph, flow there had ceased. As we will illustrate below, the feature 'C' in fig. 20 was still identifiable in 1992 as a hanging valley several tens of meters above the bed of Tahoma Creek, at about river km 11.3.

South Tahoma Glacier continued to advance until 1976 (fig. 7). From fig. 21, which shows the glacier terminus and region immediately down-valley in 1976, it appears that the geometry of the abandoned stream course (feature 'A' of fig. 21) had not changed substantially since 1972, nor had Tahoma Creek incised substantially more, at least locally. We have no conclusive reports of outburst floods or debris flows in the interim, although anecdotal accounts from NPS employees indicate there might have been a few. Scars of several slope failures are evident on the lateral moraine on the southeast side of the valley. These slumps had occurred sometime since 1973.

Documented debris flows apparently caused by outburst floods occurred next in mid-summer 1979 and August 1981 (exact dates uncertain). There are few useful aerial photographs of the Tahoma Creek drainage for those years. An oblique aerial photograph of August 17, 1981 (fig. 22), which obviously postdates the 1979 event but not definitely the one of 1981, shows a lenticular body of debris-mantled ice apparently cut off from the rest of the glacier near a constriction in the valley. Tahoma Creek appeared to pass beneath the head of the detached ice mass. Farther down-valley, two streams issued from the stagnant ice, one of them being incised into the stagnant ice. At the bottom center of fig. 22, the old outlet-stream course (linear depression 'C' of fig. 20) appears distinctly as a hanging valley for the first time in any photograph, suggesting that there had been substantial incision, perhaps 10 m or more, as a result of the 1979 (and 1981?) outburst floods.

Comparison of figs. 22 and 23 shows that there was little geomorphic change along Tahoma Creek between August 17, 1981 and September 4, 1986. The outburst floods of October 26, 1986 and the four outbursts of 1987 then caused major changes. Fig. 24 is an oblique aerial photograph taken September 28, 1987, two days after the last outburst flood of 1987. The deep incision into stagnant ice up-valley of the meander bend indicated by an arrow (at river km 11.5) had occurred during the 1986 and 1987 events. Fig. 25 is another oblique aerial photograph taken the same date but looking downstream. At the spot marked 'B' in fig. 25 (about river km 12.4), an outburst flood on 29 June 1987 incised stagnant ice (fig. 26).

Figure 20.--Oblique aerial photograph taken October 12, 1972 showing (on right) South Tahoma Glacier and upper reach of Tahoma Creek. Marked points are (A) confluence with tributary from Tahoma Glacier, (B) location of former confluence with tributary stream that issued from stagnant ice in 1967 (compare fig. 19), and (C) depression along course of latter tributary. Photographer unknown; photograph from USGS archives, Tacoma, Washington.

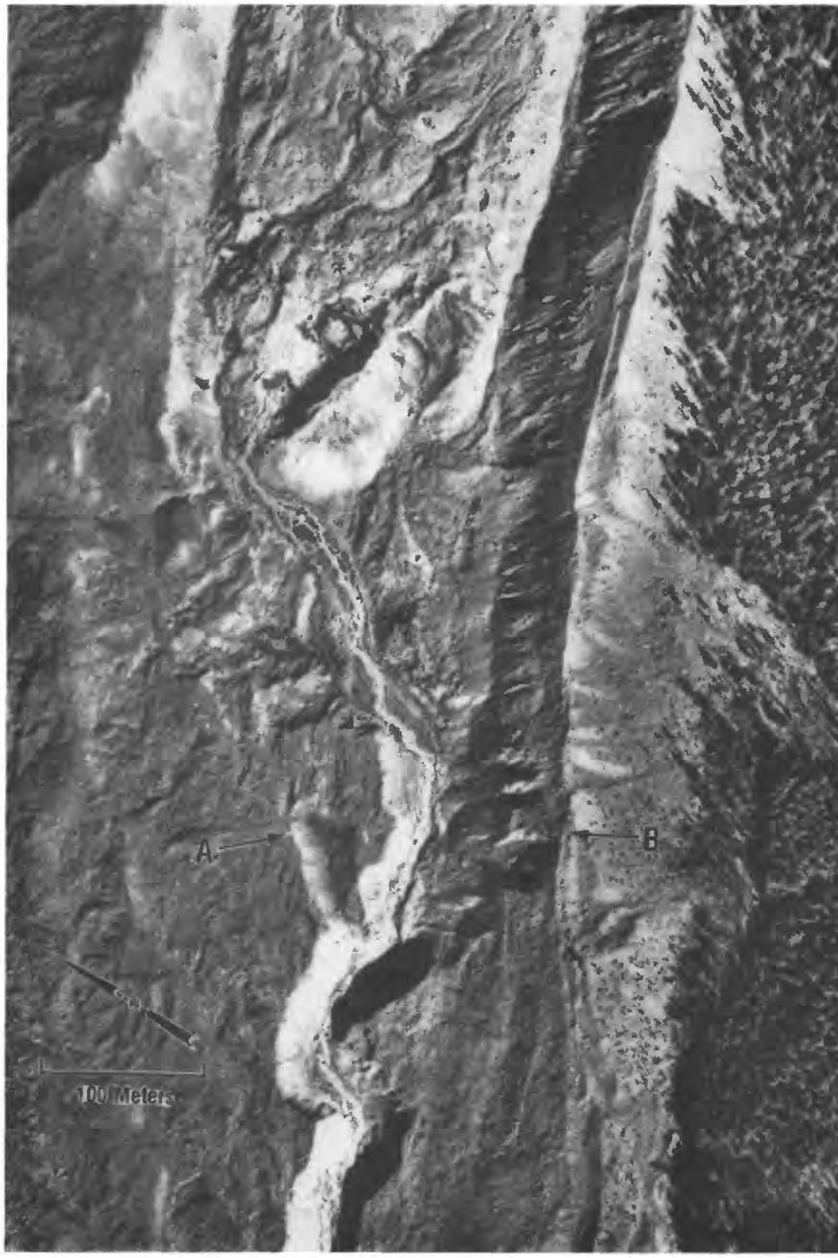


Figure 21.--Vertical aerial photograph taken September 29, 1976, showing region near terminus of South Tahoma Glacier. Marked points are (A) the abandoned course of a tributary that issued from stagnant ice in 1967, and (B) scars of slope failures from a Neoglacial lateral moraine. Upstream is towards the top. Scale is approximate. Photographer unknown; photograph from USGS archives, Tacoma, Washington.

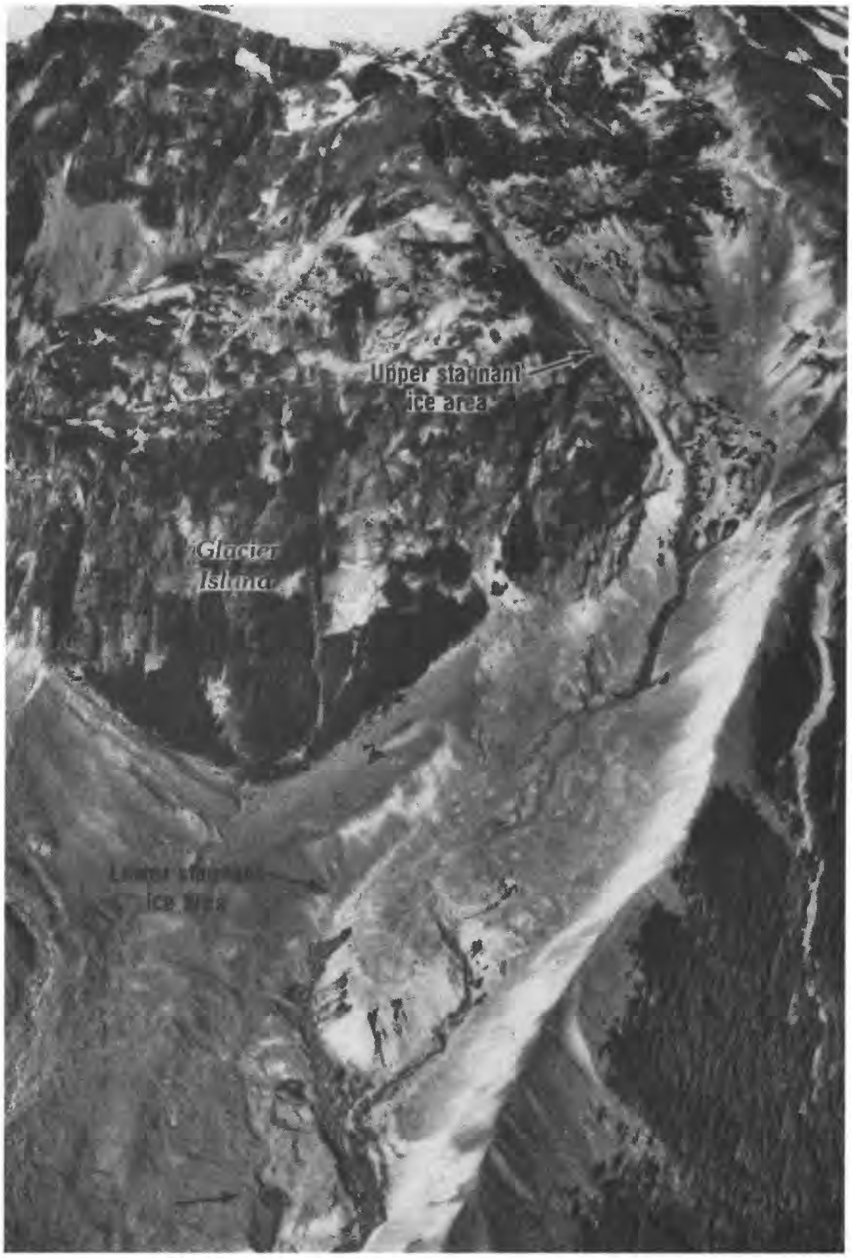


Figure 22.--Oblique aerial photograph taken August 17, 1981 showing South Tahoma Glacier and uppermost reach of Tahoma Creek. Note the morphologically distinct stagnant ice body in the valley, separated from the glacier. The abandoned course of a tributary (compare figs. 18 and 20) appears as a hanging valley above Tahoma Creek (arrow at bottom center). Photographer unknown; photograph from USGS archives, Tacoma, Washington.

Figure 23.--Oblique aerial photograph taken September 4, 1986 showing part of South Tahoma Glacier and Tahoma Creek. The stagnant ice body in the valley (arrow) is less distinct that in Fig. 22. Photographer unknown; photograph from USGS archives, Tacoma, Washington.

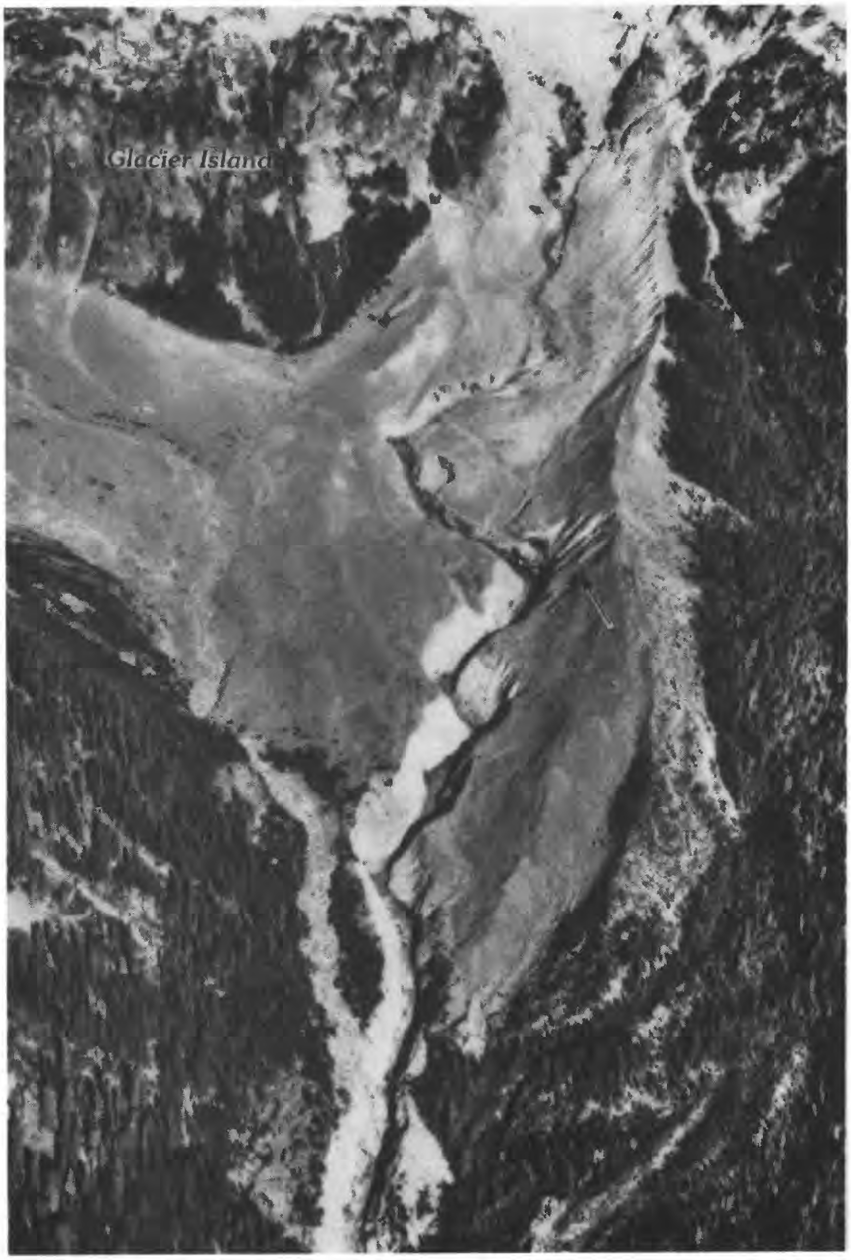


Figure 24.--Oblique aerial photograph (looking upstream) taken September 28, 1987 showing upper reach of Tahoma Creek. Incision into the stagnant ice body upstream of point indicated by arrow occurred during debris flows in 1986 and 1987. Photographer unknown; photograph from USGS archives, Tacoma, Washington.

Figure 25.--Oblique aerial photograph (looking downstream) taken September 28, 1987 showing upper reach of Tahoma Creek, essentially the same area shown in fig. 24. The snout of the stagnant ice mass (point 'A') is evident in this view. Point 'B' marks site at which stagnant ice was incised by the outburst flood of June 29, 1987. Photographer unknown; photograph from USGS archives, Tacoma, Washington.

Figure 26.--Zone of incision by Tahoma Creek into stagnant ice. This is near the point marked 'B' in fig. 25. Incision occurred during the outburst flood of June 29, 1987. Note the debris-flow levees and the sinkhole. Photograph by K.M. Scott, USGS.

Three debris flows occurred in 1988. The first two, on July 14 and July 26, happened during hot, dry weather and are therefore presumed to have been caused by outburst floods. None of the aerial photographs taken on August 21, September 13, and September 21 shows major geomorphic changes in the upper Tahoma Creek valley, suggesting that individual slope failures associated with the July, 1988 debris flows were relatively small. The debris flow of October 16, 1988, was distinctly different in this regard, as illustrated by fig. 16.

Incision and slumping in the lower stagnant-ice zone have continued since 1988, although no individual slope failure has been as large as the one shown in fig. 8. By 1992, the gorge was locally as much as 40 m deep. Two debris flows in September 1992 were associated with slumping in the reach of Tahoma Creek between about river km 10.5 and river km 11, marking the only significant slope retreat in that reach since 1987 (figs. 27, 28 and 29).

The 1992 debris flows caused incision into volcaniclastic bedrock underlying glacial deposits. Near the confluence with the tributary coming from Tahoma Glacier (river km 10.6), Tahoma Creek spills over a bedrock waterfall. That waterfall had formed during 1988 after debris flows had incised entirely through overlying glacial and laharic sediments, and had been stable until the September 1992 flows, as a result of which the waterfall retreated about 30 to 40 m upstream. A notch about 15 to 20 m in depth and width was cut into the bedrock.

Figure 27.--Vertical aerial photograph taken September 29, 1992 showing regions of bank failure during debris flows of September, 1992 along Tahoma Creek. 'A' and 'B' indicate areas of bank failure, the first such in this reach since 1987. 'C' indicates site of bedrock erosion described in text. Wonderland Trail suspension bridge is at bottom center (arrow). Upstream is towards the top. Scale is approximate. Photograph by Washington State Department of Transportation.

Figure 28.--Vertical aerial photograph taken October 28, 1988 showing deeply incised reach of Tahoma Creek. The hanging valley previously described is at 'A'. The meander nose at 'B' was removed during September, 1992 (compare fig. 29). Upstream is towards the top. Scale is approximate. Photograph by Washington State Department of Transportation.

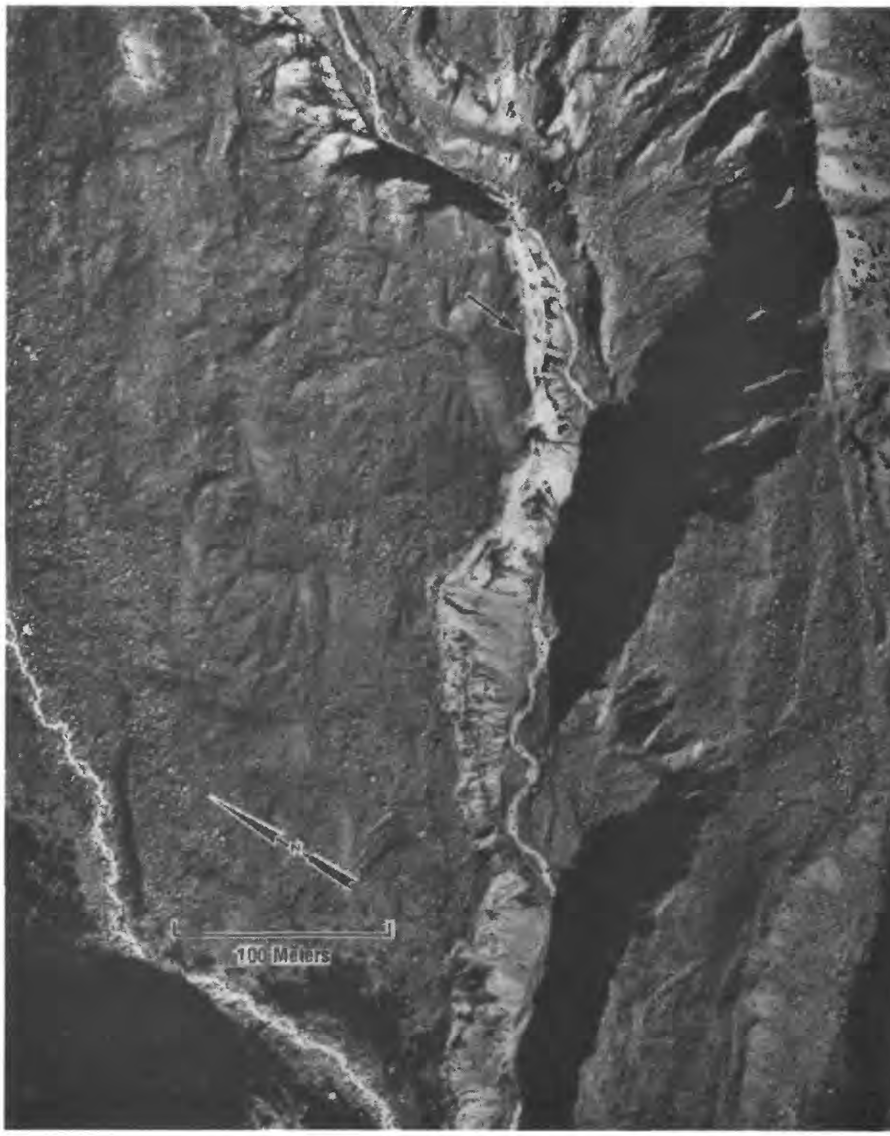


Figure 29.--Vertical aerial photograph showing bank failure associated with debris flows of September, 1992 along Tahoma Creek. Arrow indicates where the nose of a meander, volume estimated at about 10^5 m^3*, was removed. Compare to fig. 28. Upstream is towards the top. Scale is approximate. Photograph by Washington State Department of Transportation.*

Measurement of change

We determined net topographic change in the erosional zone during the period 1970 to 1991 by comparing topographic data for those areas for those two years. The 1970 topography is given by the USGS 7.5-minute topographic map for the Mount Rainier West, Washington quadrangle, dated 1971 (fig. 30). The 1991 topography is given on a map compiled by us from aerial photographs taken on September 21, 1991 (fig. 31). (Because the 1971 USGS map gave elevations in feet (ft) instead of meters, we have used units of feet for all maps.) The two maps use the same control points and the 1991 map's precision is at least as good as that of the 1970 map. At the lateral margins of the map area, chosen to be on terrain that we believe is stable, topographic contours on the two maps typically matched to within about 20 ft (about 6 m), and we suggest this is a reasonable measure of each map's accuracy.

Using the 1970 and 1991 topographic maps, we produced a map of elevation change $\Delta H = H_{70} - H_{91}$ (fig. 32), where H_{70} is elevation at a point in 1970 and H_{91} is elevation at the same point in 1991. We first digitized the topographic maps for 1970 and 1991, then used a computer program to interpolate from the digitized data to produce apparent elevation values (H_{70} and H_{91}) at regularly spaced points on a rectangular grid with approximately 50-meter spacing. We then calculated the difference between the interpolated elevations at the grid points. Given the precision of the individual maps, the probable error in ΔH, which we denote by $\varepsilon(\Delta H)$, is about $\sqrt{(20\,\text{ft})^2 + (20\,\text{ft})^2} \approx 28\,\text{ft}$. Because the glacier was advancing in 1970--the advance ended in 1976--these ΔH values must systematically underestimate the total amount of incision since the advance ended. Near the 1976 terminus, the error is probably about 50 ft (about 15 m), roughly equal to the greatest apparent thickening in that zone; farther up-valley, the error must be less, because the glacier's surface sloped relatively gently away from the terminus. Negative values of ΔH indicate areas of elevation gain since 1970--that is, areas over which ice advanced between 1970 and 1976. The region of deep incision during and since the 1986 event is clearly marked in fig. 32 as a curvilinear zone with ΔH typically in the range 50 to 125 ft (about 15 to 40 m).

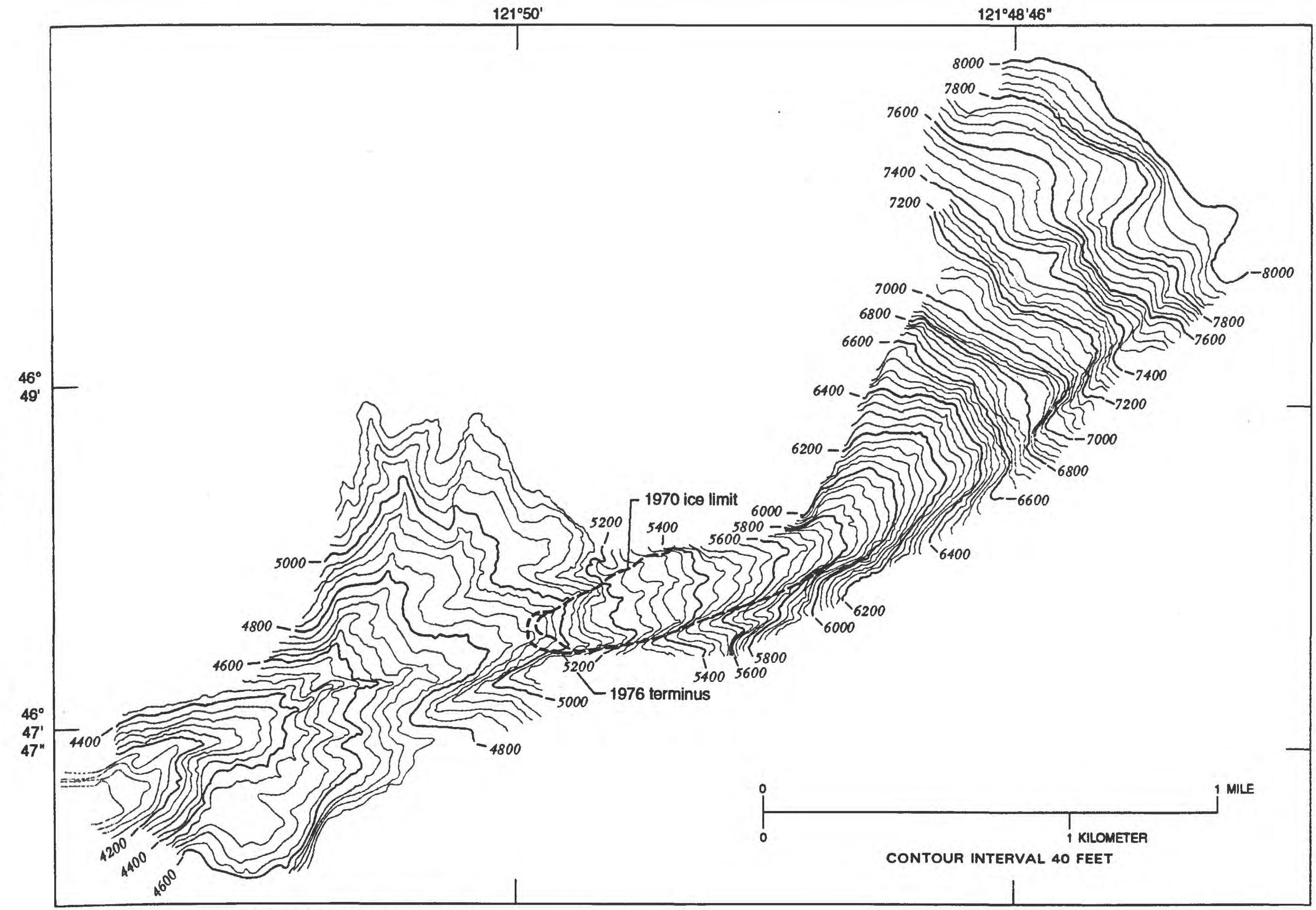
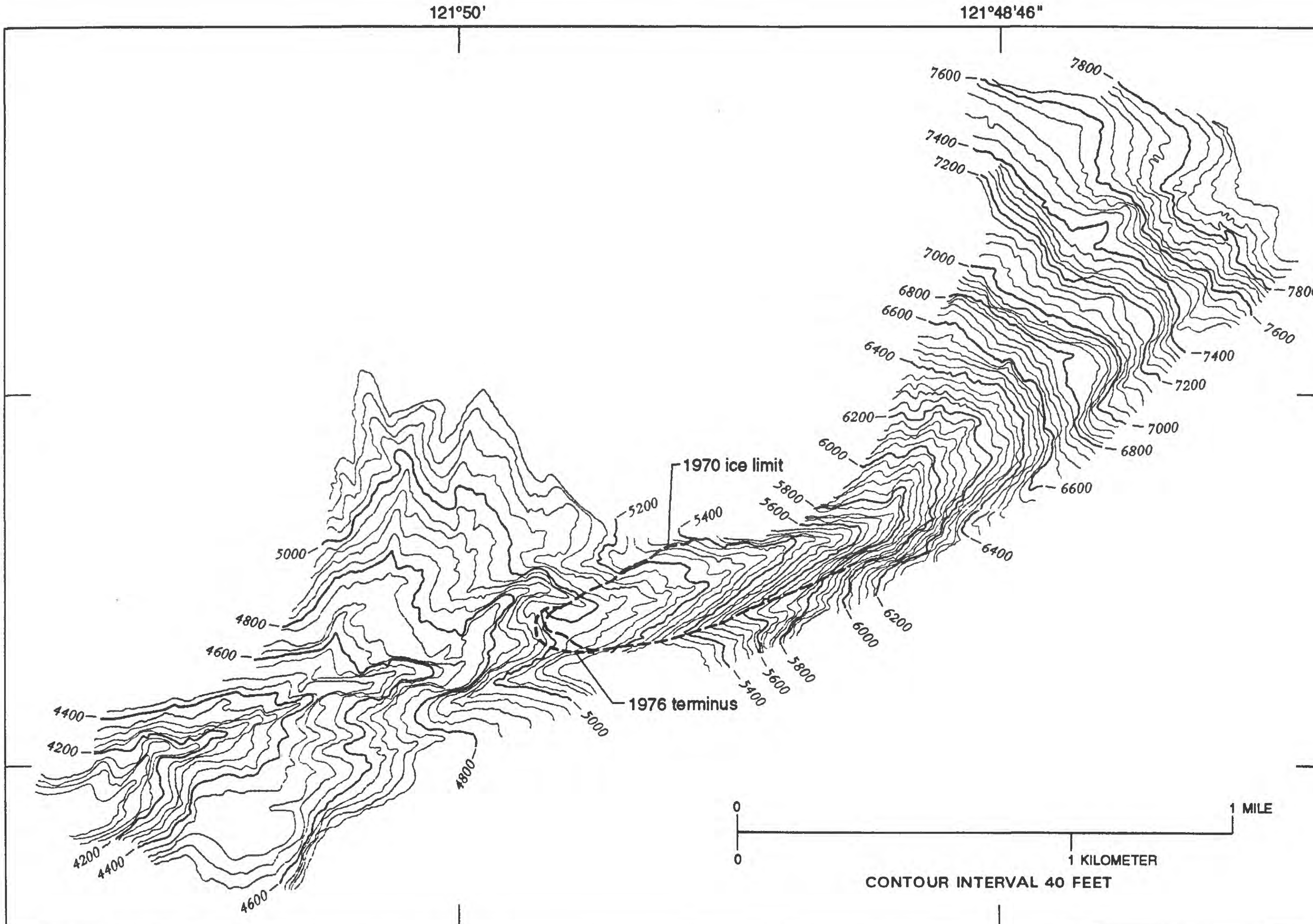
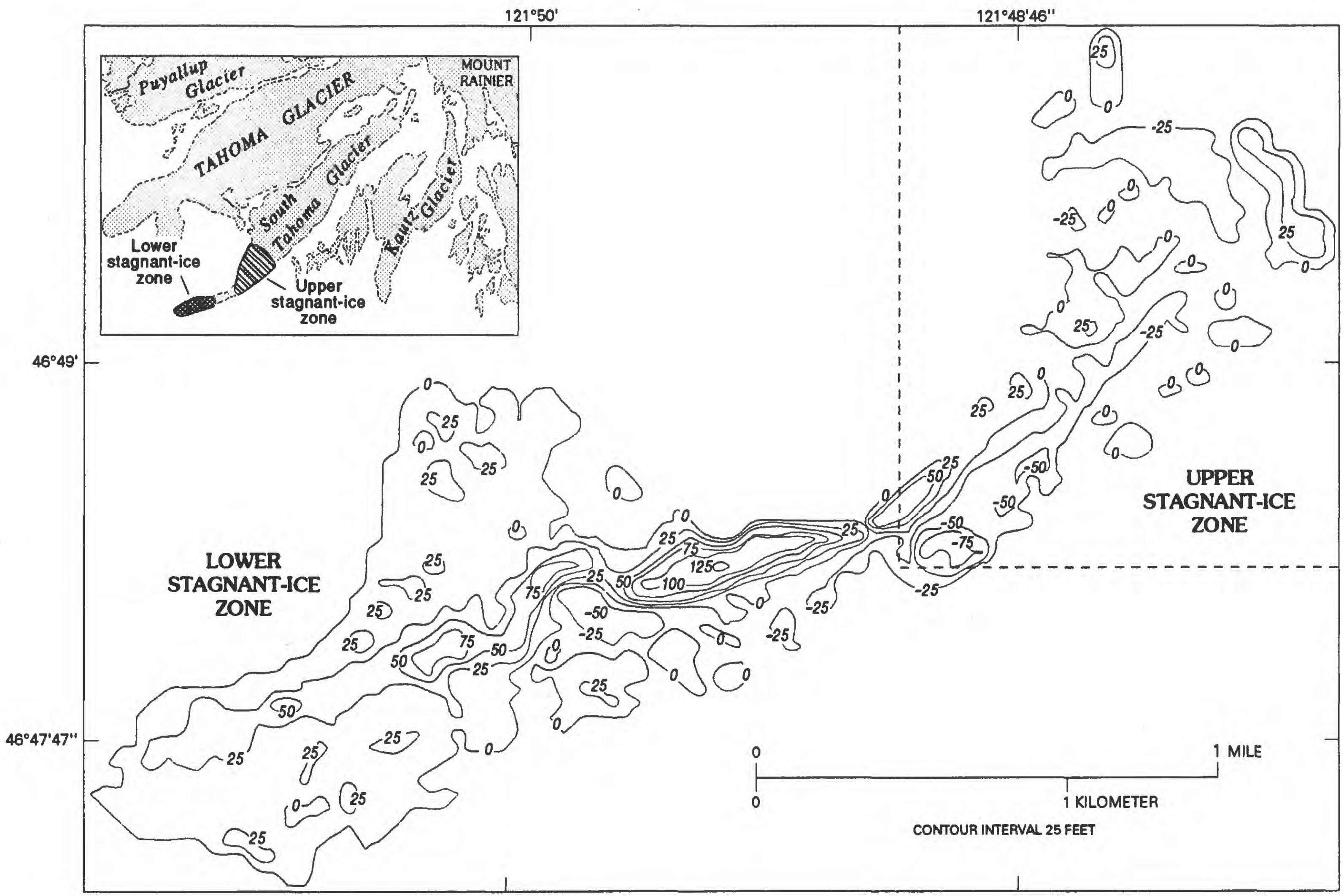


Figure 30.--Topography in 1970 of upper reach of Tahoma Creek and part of South Tahoma Glacier. Glacier-terminus positions in 1970 and 1976 are indicated.



Topography by U.S. Geological Survey
from aerial photographs taken in 1991

Figure 31.--Topography in 1991 of same area as shown in fig. 30. Glacier-terminus positions in 1970 and 1976 are indicated.



Contours derived from difference between 1971 map (U.S. Geological Survey, Mount Rainier West) and 1991 map (topography by photogrammetric methods, prepared and edited by U.S. Geological Survey), using digitization and numerical interpolation methods

Figure 32.--Map of topographic change between 1970 and 1991 in the map area shown in figs. 30 and 31.

From the map of elevation change, we calculated a volume change ΔV_u in the upper stagnant-ice area of approximately -3.7×10^6 m^3, the negative sign indicating overall thickening. This area has only a veneer of rock debris, so ΔV_u indicates that the ice was locally thicker in 1991 than in 1970. Volume change ΔV_l in the lower stagnant-ice area between 1970 and 1991 was 9.2×10^6 m^3. The probable errors in these figures are hard to quantify. Denoting the error in volume change by $\varepsilon(\Delta V)$, we have

$$\frac{\varepsilon(\Delta V)}{|\Delta V|} = \frac{\varepsilon(\Delta H)}{|\Delta H|} \tag{1}$$

for any "cell" in the interpolation grid. With $\varepsilon(\Delta H) \approx 9$ m and $|\Delta H| <$ about 40 m, we have $\varepsilon(\Delta V)/|\Delta V| \approx 0.2$ in the most deeply incised area. The probable error would be an even larger fraction of $|\Delta V|$ in areas with smaller $|\Delta H|$. Thus the probable random errors in the estimates ΔV_l, ΔV_u are at least 20 percent and could be either positive or negative. In addition, as mentioned before, our calculated ΔV_l systematically underestimates actual volume loss, owing to unavoidable use of the 1970 topographic map as the basis for comparison. This systematic error is probably about 20 to 30 percent. We conclude that our estimate of ΔV_l is more likely to be an underestimate than an overestimate.

The value of ΔV_l since the onset of debris-flow activity in 1967 almost certainly exceeds 10^7 m^3; the average rate of volume change was therefore at least 4×10^5 m^3/a during the period 1967 to 1991. An uncertain fraction of ΔV_l, very likely 50% or less, comprised glacier ice. Deposits from debris flows in 1986 and 1987, and from some in 1988, contained occasional blocks of glacier ice (Scott et al. (1992) and our observations), although some or all could have come from the upper stagnant-ice area. We have read no reports of glacier ice within debris-flow deposits formed before 1986, nor have we seen glacier ice within deposits of 1989 to 1992. This near-absence of glacier ice within recent deposits is perplexing, because morphological evidence from aerial photographs indicates that much of the source area was part of a glacier as recently as 1976, and there are some outcrops of glacier ice visible at present.

The volume V_{sf} of an individual slope failure can be estimated by measuring (on an aerial photograph) the plan area of slumped material and estimating its vertical extent and shape. The two largest individual slope failures during the period 1988 through 1992--the one of October 16, 1988 (fig. 16) and one in September 1992 (fig. 29)--had $V_{sf} \approx 10^5$ m^3. Though not all slope failures have been equal in size, it is noteworthy that these estimates of V_{sf} are of the same order of magnitude as the average annual volume change in the lower stagnant-ice area. Clearly slump blocks entrained by outburst floods have accounted for a significant fraction of the total sediment removed from this area.

Slope retreat

Mechanisms of slope retreat in the lower stagnant-ice area are complicated. Debris-covered stagnant ice in alpine environments may survive for several hundred years (Driscoll, 1980; Mattson and Gardner, 1991; Johnson, 1992). Ablation by heat conduction through a thick mantle of rock debris is practically negligible (e.g., Driedger (1981) or Lundstrom (1992)). Melting of buried ice is greatly accelerated when slumps of the debris mantle expose buried ice. In the lower stagnant-ice zone, the critical factor in exposing buried ice and speeding its decay has been deep incision caused by outburst floods. This process is similar to development of retrogressive thaw slumps in permafrost (French, 1974; Harris and Gustafson, 1988). Slope retreat in the lower stagnant-ice area is not, however, solely a function of the rate of ice wastage, because the overall ice content seems to be low and there seem to be significant ice-free domains. Moreover, there is potential for slope retreat and instability in morainal deposits bordering the stagnant-ice zone, as borne out by the flowslide of October 16, 1988 (fig. 8).

On visits to the lower stagnant-ice area during summer, we saw abundant evidence of slumping, including tension cracks (fig. 33) and masses of sediment that had slid downhill but then temporarily stabilized (fig. 34). Rates of slope retreat were spatially quite variable. Stakes placed in the ground in this area in 1989 and 1990, within about 0.5 m of the edge of the gorge, were missing in June 1992.

Except when flood waters were initiating incision in any given reach, water depth must have been much less than the depth of the gorge, so we suggest slump blocks were destabilized by erosion of their toes, and perhaps by ground shaking as flood waters passed. Slope instability along Tahoma Creek might also be due in part to ground-water seepage (for example, Bromhead (1986) and Iverson and Major (1986)). Buried ice is likely to enhance the likelihood of seepage-driven slope failure. At Tahoma Creek, such ice rarely crops out on the gorge walls, but rather is covered by sediment. Ground water encountering buried ice would be deflected toward a neighboring ice-free zone. If such deflection happens to be in the direction of the free surface, the seepage force exerted on the sediment would have a destabilizing effect.

Figure 33.--Tension crack at surface of lower stagnant-ice zone of South Tahoma Glacier. Arrow at center shows gap of about 0.1 meter between a clast and neighboring morainal material. Note pack and shirt at lower right for scale.

Figure 34.--Slump features in lower stagnant-ice zone along Tahoma Creek. Arrow indicates ground-surface expression of a slip surface. The largest angular boulder at lower left is about 1 meter long.

Depositional zone

Bouldery sediment moved downstream by debris flows since 1967 has been deposited over a reach between about river km 9 and river km 5. Sand, silt and clay have often been carried as far as the highway bridge (river km 1) by the watery recessional phase of debris flows. Sedimentology of Tahoma Creek debris-flow deposits is more fully described by Scott and others (1992, p. 61-66). Probably little of the sediment moved by debris flows--and almost certainly none of the bouldery fraction--has reached the mouth of Tahoma Creek and then entered the Nisqually River.

Deposit thickness for any particular debris flow is quite variable in space, even transverse to the flow direction. Usually distinct levees are formed. In the depositional reach, the stream channel is not closely constrained by valley walls; thus a debris flow may initially follow the route of the existing stream, but typically avulses when the flow spills over the channel's banks or when deposition plugs the existing channel. The net result since 1986 has been more or less uniform aggradation transverse to the mean stream course. We estimate that since 1988 about 2 m of bouldery sediment, on average, has been deposited over much of the reach between river km 9 and river km 5. The total volume of these deposits is about $0.5 - 1 \times 10^6$ m^3. The largest debris flows during the period 1988 to 1992 each left about 10^5 m^3 of bouldery deposits.

Large quantities of sand and silt have been deposited beneath the Nisqually-Longmire Road bridge across Tahoma Creek (fig. 6). Part of this sediment is presumably derived by normal stream action, with sediment supply augmented by the abundance of glacially derived material in the upper reaches, but most probably represents the dewatering phase (often hyperconcentrated flow) of debris flows (Scott and others, 1992). To protect the bridge from potential flood damage, NPS has occasionally removed sediment accumulating beneath the bridge.

Many stands of trees have been killed or are dying because of debris flows (fig. 35). A relatively small fraction of these trees were killed outright: they were broken at or near ground level by the force of impacting debris flows, or toppled from banks eroded by passing debris flows. In most cases, however, damage and slow death has resulted from burial of the lowermost trunk plus perhaps abrasion of exposed bark. The Tahoma Creek trail has been obliterated where it passed through damaged forest areas between about river km 7.5 and river km 8.5. Those areas are now cut by gullies and littered with boulders and downed trees, making passage on foot difficult and hazardous.

Figure 35.--Heavily damaged forested area in the floodplain of Tahoma Creek, within the zone of boulder deposition. Many dead trees are still standing.

Comparison to change in other glacierized drainages

Substantial glacier retreat from Little Ice Age maxima is ubiquitous in alpine areas, and stagnant ice in valleys below present-day glaciers is also common, yet geomorphic change along Tahoma Creek in comparison to other drainages has been extremely rapid. The rate of incision in the lower stagnant-ice zone from 1967 to 1991, if averaged over the entire drainage basin upstream of the zone of conveyance--an area of about 10 square kilometers (km^2)--corresponds to an extremely high local denudation rate of at least 40 millimeters per year (mm/a). Even if half of the material removed has been ice--and this is probably an overestimate--the average denudation rate in the upper part of the drainage basin has been extraordinary. Clearly outburst floods from South Tahoma Glacier have been exceptionally effective at moving sediment. Yet the Tahoma Creek drainage basin is similar to some other basins affected by debris flows (Osterkamp and Costa, 1986) in that very little of the sediment so transported has left the basin. The total sediment load of the Nisqually River, of which Tahoma Creek is a tributary (fig. 1), corresponds to a denudation rate of only about 3 mm/a for the $30\,km^2$ part of the Nisqually River drainage basin on Mount Rainier (Mills, 1976).

We now compare in more detail geomorphic change along Tahoma Creek to changes along two other glacier-fed streams: the unnamed outlet stream flowing in "Cathedral Gulch" (informal name) below Cathedral Glacier, British Columbia, Canada, and the Nisqually River below Nisqually Glacier, also on Mount Rainier. In both of these places, stagnant ice stranded by retreat from the Little Ice Age maximum has been affected by outburst floods, but with rather different results.

Description of the "Cathedral Gulch" debris flows is based on the work of Jackson et al. (1989). Retreat of Cathedral Glacier from its Little Ice Age maximum left debris-rich ice stranded on the steep ($20°$ to $30°$) slopes of Cathedral Mountain. The shrunken glacier impounded a small subaerial lake. Sizable debris flows formed near the terminus of Cathedral Glacier have on 7 occasions since 1925 blocked Canadian Pacific Railroad tracks. Four of these flows occurred on dry days and were triggered by glacial outburst floods, and at least 1 of the 3 wet-weather flows was also triggered by an outburst flood. Incision by the floods has created "Cathedral Gulch," which is cut as much as 8 m deep in rockfall talus and debris-rich stagnant ice. About 1 to $2 \times 10^6\ m^3$ of material has been eroded and subsequently deposited on a broad fan below the "gulch." The last debris flows occurred on August 27 and 29, 1984. There have been no further outburst floods since the ice-dammed lake, which provided most of the water released in outburst floods--the rest being subglacially stored--was pumped dry in 1985 and 1986.

Each of the four largest "Cathedral Gulch" debris flows moved about 10^5 m^3 of sediment, about the same volume as in the largest debris flows at Tahoma Creek during the period of our investigation (1988 to 1992). (A few of the 1986 and 1987 debris flows at Tahoma Creek were probably several times as large (K.M. Scott, personal communication).) The similarity of debris-flow volumes at the two locations, despite significant differences in frequency of outburst floods and slope of the eroded reach at the two sites, may simply reflect the fact that the length of the eroded reach is about 2 km at both "Cathedral Gulch" and Tahoma Creek. Another factor possibly bearing on the size of the debris flows is the nature of the substrate: at both sites, it consists largely of debris-rich stagnant ice.

In contrast to "Cathedral Gulch", along the Nisqually River near the terminus of Nisqually Glacier, 9 documented water floods or debris flows, probably all originating as outburst floods from the glacier, have moved along the Nisqually River since 1926 (Driedger and Fountain, 1989), yet there is not a gorge developed in the stagnant ice in front of the glacier. Stagnant ice in front of the advancing terminus was significantly eroded by the October 25, 1955 flood (figs. 36 and 37)--perhaps comparable to erosion along Tahoma Creek by the September 18, 1967 outburst flood (figs. 18 and 19)--so the potential for geomorphic development as along Tahoma Creek probably existed. However, the next outburst did not occur until 1968 (Hodge, 1974). K.M. Scott (personal communication, 1993), who has inspected deposits left by that flood, as well as deposits of subsequent floods in 1970 and 1972, believes on sedimentological grounds that none of them transformed to debris flows. A photograph taken September 10, 1975 (fig. 38) showed no sign of the stagnant-ice gullies present in 1956 (fig. 37). Because channel slope and nature of the incised material were very similar at Tahoma Creek and the Nisqually River, we suggest that the lack of gorge development along the Nisqually River was due to the relative infrequency of outburst floods from Nisqually Glacier, as compared to South Tahoma Glacier. The Nisqually River may have come to "equilibrium" with outburst floods as the salient channel-forming events (compare Desloges and Church, 1992).

On the basis of the comparisons presented above, we suggest that 3 factors having a crucial effect on recent geomorphic evolution in glacierized alpine basins are (1) frequency of extreme hydrologic events, such as outburst floods; (2) channel slope; and (3) nature of the stream's substrate. Debris-rich stagnant ice is easily incised by floods, and if a gorge is developed, slope failures from channel walls can supply sediment for debris flows. However, a gorge can be maintained only if floods are relatively frequent (as at Tahoma Creek) or if channel slope is so great that sediment sloughing from channel walls is easily mobilized (as at "Cathedral Gulch").

Figure 36.--Area near terminus of Nisqually Glacier on September 3, 1955. The glacier at the time was advancing over debris-covered stagnant ice. Photograph by F.M. Veach, USGS.

Figure 37.--Area near terminus of Nisqually Glacier on August 30, 1956. Channels in debris-covered stagnant ice had been cut or deepened by the outburst flood of October 25, 1955. Compare to fig. 36. Photograph by F.M. Veach, USGS.

Figure 38.--Area near terminus of Nisqually Glacier on September 10, 1975. Although there had been outburst floods in 1968, 1970, and 1972, there is no sign of a gorge in the valley of the Nisqually River near the terminus. Photograph by F.M. Veach, USGS.

CAUSE OF OUTBURST FLOODS

Relation between outburst floods and meteorological variables

All outburst floods from South Tahoma Glacier since 1967 have occurred during either summer or early autumn, as noted also by Driedger and Fountain (1989) and Scott et al. (1992). Anecdotal evidence indicates that weather at the time of, or shortly before, the occurrence of debris flows was either (1) abnormally hot and dry, or (2) rainy at times when there was little snow on the ground. To assess rigorously whether the outburst floods have been associated with atypical weather conditions, and whether meteorological data might be useful predictors of outburst-flood occurrence, we did a statistical analysis of meteorological data collected near South Tahoma Glacier. We restricted the analysis to the period since 1986, because flood dates tend not to be accurately known for earlier years.

Values of precipitation (R) and maximum daily temperature (T_{max}) are readily available for the Paradise Ranger Station, which lies about 7 km southeast of South Tahoma Glacier (fig. 1). Our analysis used data for the months May through November for the years 1986 through 1992 (U.S. National Oceanic and Atmospheric Administration, 1986-1992). These months approximately encompass the typical ablation season for glaciers on Mount Rainier, which like the rest of western Washington has a modified Mediterranean climate: except for occasional thundershowers, rainstorms are relatively infrequent during the summer. Actual outburst-flood dates ranged from June 29 to November 9.

The statistical distributions of rainfall and maximum daily temperature at the Paradise Ranger Station are shown in figs. 39 and 40. (Days with measurable snowfall were excluded in compiling these figures.) The solid curve in each figure is the cumulative distribution function (henceforth CDF); the crosses connected by dashed lines show the distributions for days on which outburst floods from South Tahoma Glacier occurred. We now pose the question: What is the probability that the distributions of meteorological data <u>for days on which outburst floods occurred</u> are drawn at random from the CDF's? We use the Kolmogorov-Smirnov test of goodness of fit (Conover, 1971) to find an answer. The test statistic d_m is the largest vertical distance between the CDF and the stepwise sample curve connecting values measured on days of outburst-flood occurrence (figs. 39 and 40). For a given number n of data points in the sample population, one may calculate the probability P that for another sample of n points the largest vertical distance between the curves would exceed the measured value d_m. P may also be interpreted as the probability that the sample population (in our case, days with outburst floods) is drawn at random from the parent population (all snow-free days from May through November). The Kolmogorov-Smirnov test is preferred to the chi-square test for small sample sizes, as in the case of outburst floods, because it does not assume a Gaussian distribution of the test statistic (Conover, 1971).

Results are shown in the top halves of Tables 1 and 2 for the cases illustrated by figs. 39 and 40, as well as for analogous tests using 2-, 3-, and 4-day moving averages of maximum daily temperature and rainfall. (For moving averages, the last day of the averaging period is always the day of the flood.) We conclude that values of rainfall and maximum daily temperature for days with outburst floods are unlikely to be drawn from the parent population, although this conclusion weakens as we consider progressively longer averaging periods. Thus outburst floods appear to coincide with atypical weather.

We may make stronger statements once we note that there are two distinct subpopulations in the data for days with outburst floods: warm, dry days ($T_{max} > 20\ °C,\ R = 0$) and cool rainy days ($T_{max} < 15\ °C,\ R > 0$). We therefore consider the statistical distributions of rainfall only on days with measurable rainfall (fig. 41) and of maximum temperature on rainless days (fig. 42). Results are presented in the bottom halves of Tables 1 and 2, for tests using daily data and moving averages, as before. Values of P are in some cases less than 0.001.

On the basis of these tests of goodness of fit, we conclude that outburst floods from South Tahoma Glacier are highly correlated with atypical weather. In particular, it is clear from figs. 41 and 42 that outburst floods have occurred generally on days of relatively heavy rain or high temperatures.

The conditional probability P_c of an outburst flood from South Tahoma Glacier, as a function of R and T_{max} during the years 1986 to 1992, for the two subpopulations noted above, is shown in figs. 43 and 44. The conditional probability is the relative frequency of flood occurrence given a particular value of R or T_{max}. For example, the probability of an outburst flood on any day with ≥ 40 mm of rain was about 0.22. There are fairly clear relations between P_c and either R or T_{max} measured on the day of a flood; for progressively longer averaging periods, the trends are not so obvious, owing at least partially to the fact that averaging "compresses" the range of R and T_{max}. Data shown in figs. 43 and 44 are not necessarily predictive of outburst-flood probabilities, however, because the glacier--including, presumably, its drainage system--is changing with time, making the statistical problem nonstationary.

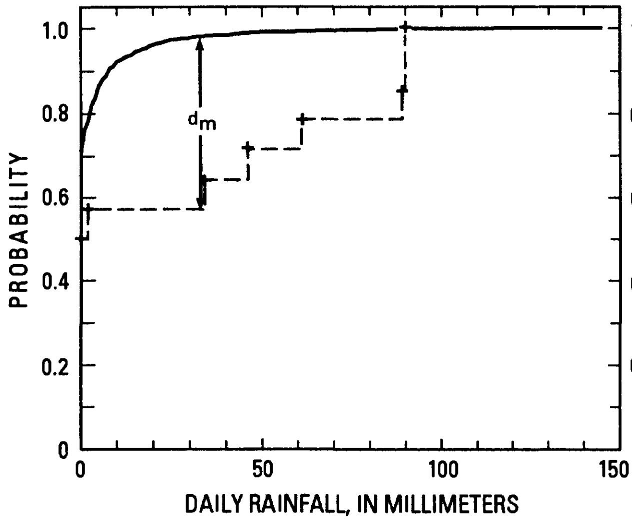


Figure 39.--Probability distribution functions for daily rainfall measured at Paradise Ranger Station, Mount Rainier, for months May through November in the years 1986 through 1992.

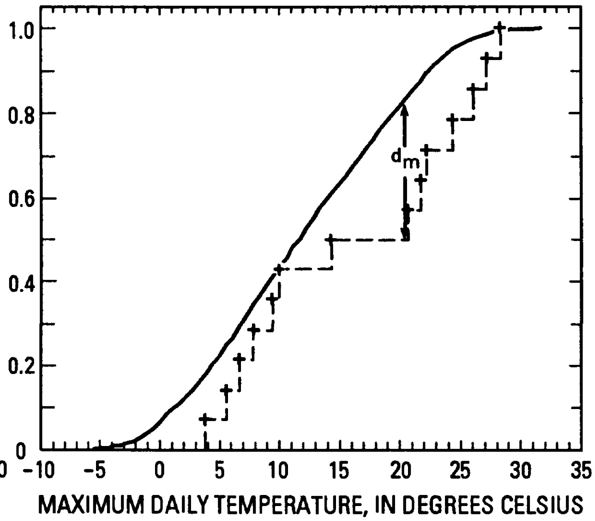


Figure 40.--Probability distribution functions for daily maximum temperature measured at Paradise Ranger Station, Mount Rainier, for months May through November in the years 1986 through 1992.

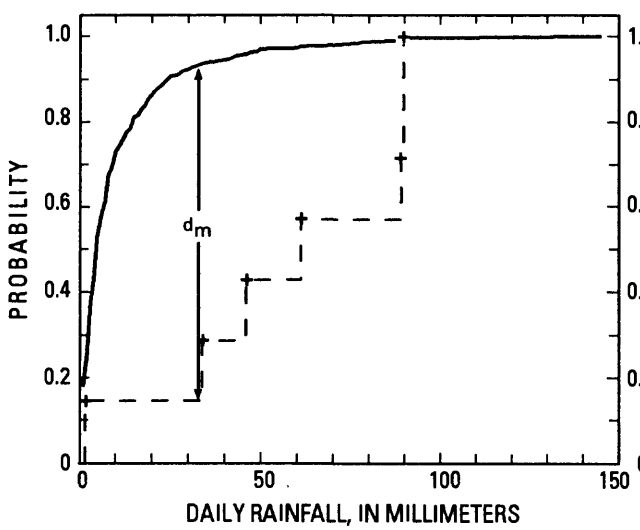


Figure 41.--Probability distribution functions for daily rainfall measured at Paradise Ranger Station, Mount Rainier, for months May through November in the years 1986 through 1992, including only days with measurable rainfall.

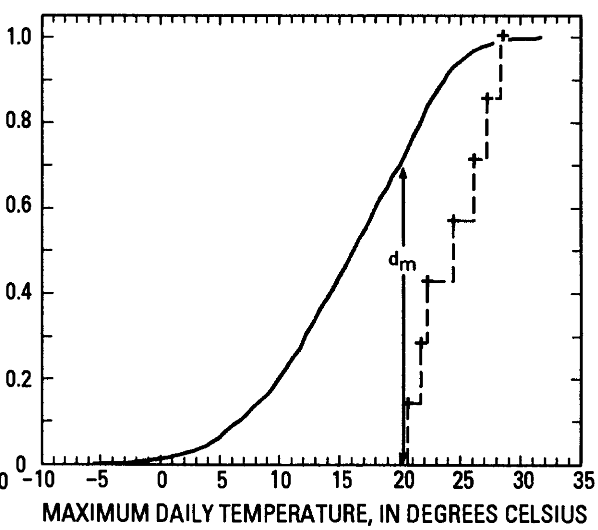


Figure 42.--Probability distribution functions for daily maximum temperature measured at Paradise Ranger Station, Mount Rainier, for months May through November in the years 1986 through 1992, including only rainless days.

EXPLANATION

\+ Debris-flow days —— Parent distribution ---- Debris-flow distribution

TABLE 1.--Results of Kolmogorov-Smirnov (K-S) test for rainfall data from Paradise Ranger Station. Meteorological data used in the analysis are for the months May to November in the years 1986 to 1992. One outburst flood for which the exact date is uncertain was excluded from the analysis. The K-S statistic is defined in the text and illustrated in fig. 39.

Type of rainfall data	Number (n) of outbursts in sample	K-S statistic (d_m)	Probability that d_m would be exceeded by another sample of n points	Notes
Daily, all snow-free days	14	0.408	6.36×10^{-3}	
Daily, all snow-free days	13	0.364	2.36×10^{-2}	Excludes October 16, 1988 flow
Daily average, all 2-day snow-free periods	14	0.346	3.38×10^{-2}	
Daily average, all 3-day snow-free periods	14	0.329	4.71×10^{-2}	
Daily average, all 4-day snow-free periods	14	0.260	3.32×10^{-1}	2-sided K-S test applies
Daily, snow-free days with measurable rain	7	0.787	2.08×10^{-5}	
Daily, snow-free days with measurable rain	6	0.763	1.86×10^{-3}	Excludes October 16, 1988 flow
Daily average, 2-day snow-free periods with measurable rain	6	0.737	3.70×10^{-4}	One flood dropped due to snow in averaging interval
Daily average, 3-day snow-free periods with measurable rain	6	0.715	6.32×10^{-4}	One flood dropped due to snow in averaging interval
Daily average, 4-day snow-free periods with measurable rain	6	0.532	4.18×10^{-2}	One flood dropped due to snow in averaging interval; 2-sided K-S test applies

TABLE 2.--Results of Kolmogorov-Smirnov (K-S) test for maximum-temperature data from Paradise Ranger Station. Meteorological data used in the analysis are for the months May to November in the years 1986 to 1992. One outburst flood for which the exact date is uncertain was excluded from the analysis. The K-S statistic is defined in the text and illustrated in fig. 40.

Type of temperature data	Number (n) of outbursts in sample	K-S statistic (d_m)	Probability that d_m would be exceeded by another sample of n points	Notes
Daily, all days	14	0.317	4.73×10^{-2}	
Daily average, all 2-day periods	14	0.293	1.48×10^{-1}	2-sided K-S test applies
Daily average, all 3-day periods	14	0.279	9.32×10^{-2}	
Daily average, all 4-day periods	14	0.257	2.66×10^{-1}	2-sided K-S test applies
Daily, all dry days	7	0.702	2.80×10^{-4}	
Daily average, all 2-day dry periods	7	0.600	3.09×10^{-3}	
Daily average, all 3-day dry periods	7	0.534	1.09×10^{-2}	
Daily average, all 4-day dry periods	6	0.582	9.32×10^{-3}	Dropped one flow due to rain in averaging period

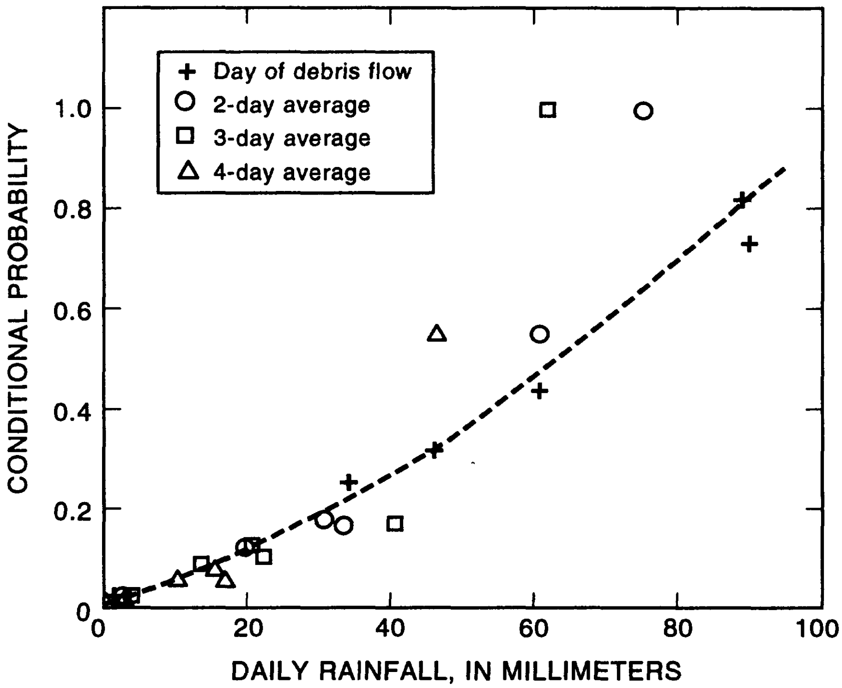


Figure 43.--Conditional probability of debris flows at Tahoma Creek as a function of daily rainfall measured at Paradise Ranger Station, including only days with measurable rainfall, from 1986 through 1991.

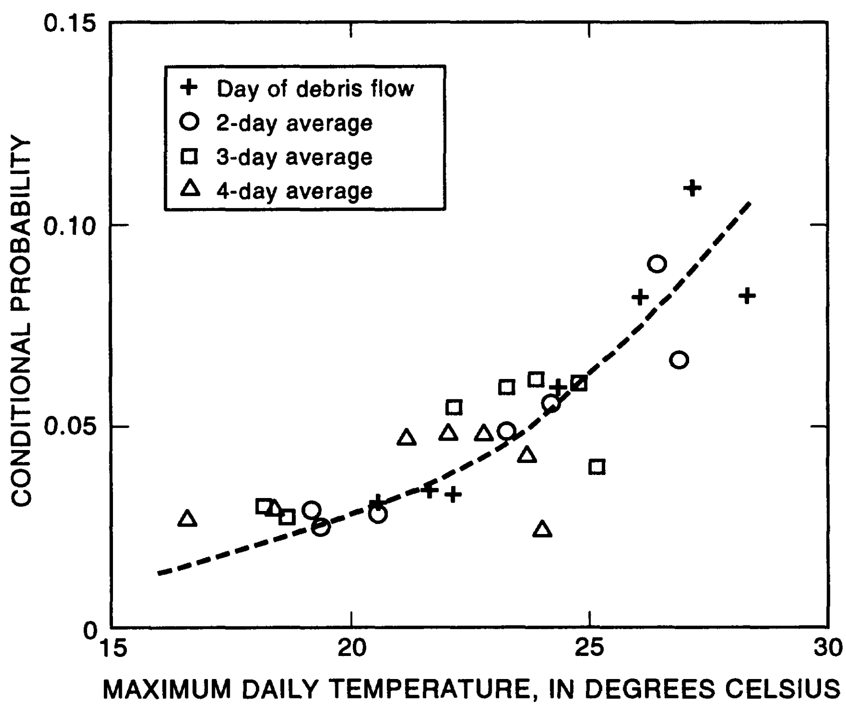


Figure 44.--Conditional probability of debris flows at Tahoma Creek as a function of daily maximum temperature measured at Paradise Ranger Station, including only rainless days, from 1986 through 1991.

If rainfall and maximum daily temperature measured at Paradise are rough proxies for rate of water input to South Tahoma Glacier, the conditional probabilities shown in figs. 43 and 44 are reasonably consistent with each other. To see this, consider that a plausible value for the ablation rate at South Tahoma Glacier on the hottest summer days (when $T_{max} \approx 30\,°C$ at Paradise) is perhaps 40 millimeters per day (cf. Fountain, 1992). From figs. 43 and 44, we find (extrapolating from the dashed curves) $P_c \approx 0.13$ for $T_{max} \approx 30\,°C$, $P_c \approx 0.22$ for $R = 40\,mm$. In light of the surrogate nature of the meteorological data, the two probabilities are remarkably similar. We therefore suggest the following physical interpretation, elaborated in the next section: Outburst floods from South Tahoma Glacier are meteorologically driven, with the probability of an outburst flood determined primarily by the rate of water input to the glacier.

We also explored whether logistic regression (Agresti, 1983) would provide a useful tool for predicting the likelihood of debris flows on the basis of meteorological data. Logistic regression is an appropriate statistical method for cases in which the explanatory variables--in the present case, temperature and precipitation--are continuous, but the response variable--here, debris-flow occurrence--is categorical, taking on the value of either 0, if a debris flow occurred on a given day, or 1, if no debris flow occurred. The logistic-regression model is an S-shaped curve (fig. 45). For a given vector of explanatory variables $\vec{X}$, the probability p of a 0 response is

$$p = \frac{1}{1 + \exp(\alpha + \vec{\beta} \cdot \vec{X})} \qquad (2)$$

where α is a constant and $\vec{\beta}$ is a vector of coefficients. (For a univariate regression, $\vec{\beta}$ becomes the scalar β.) We did both single- and multiple-variable regressions, using as explanatory variables daily values of rainfall, maximum temperature and minimum temperature; we also tried regressions using 3-, 4-, and 5-day moving averages for these variables. The moving averages were lagged; for example, for a three-day moving average, the value of the variable assigned to day N was the average value of that variable for days N-2, N-1, and N. Values of the regression coefficients are given in Table 3.

Results indicate that predictions based upon meteorological variables would not be particularly useful in an operational sense. Calculated (predicted) probabilities of debris-flow occurrence do increase, as expected, as precipitation, minimum temperature, and maximum temperature increase. The calculated probability of a debris flow is typically rather small even for the most extreme values of the explanatory variables within our data. For example, for the univariate analysis using daily values of T_{max}, the calculated probability of a debris flow is only about 4.9 percent for $T_{max} = 31.7\,°C$, the greatest value of T_{max} measured during the period of record. Calculated probabilities of a debris flow using the most extreme values of T_{max} for the various moving averages were only about 6 percent. In the univariate analysis utilizing precipitation, the calculated probability of a debris flow for the most extreme value

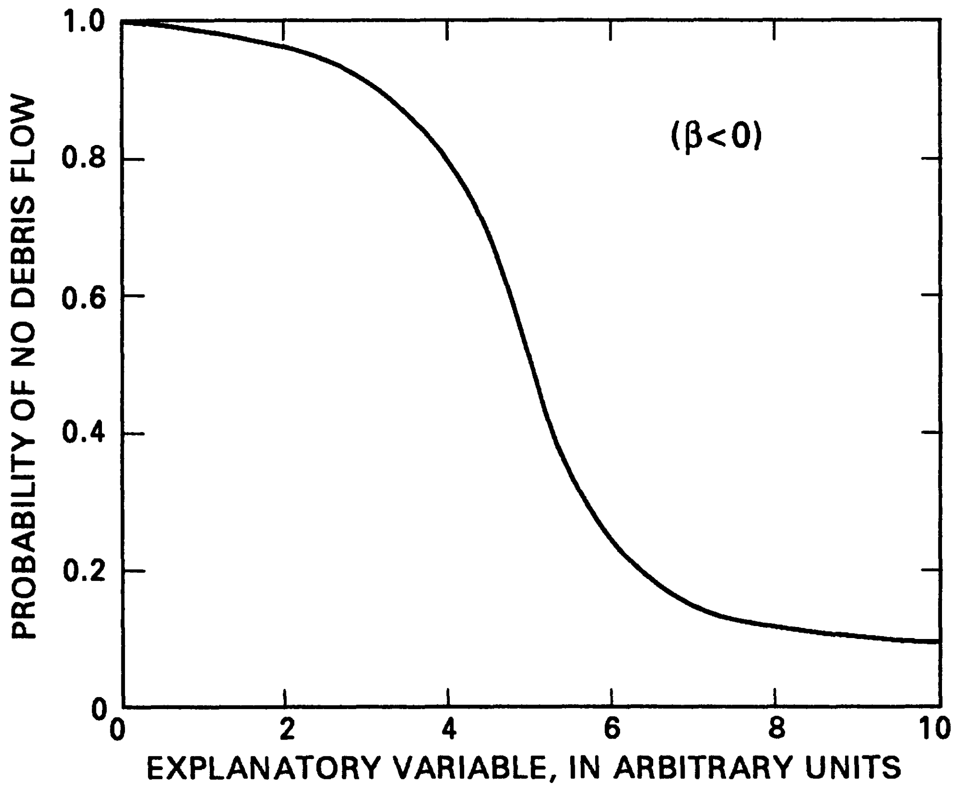


Figure 45.--The idealized model fitted by logistic regression.

of p was 29.5 percent using daily precipitation as explanatory variable, but fell monotonically as we considered, respectively, 3-, 4- and 5-day moving averages. Calculated probabilities are somewhat greater for extreme values of the meteorological variables for the multivariate analyses.

Probabilities of debris-flow occurrence calculated by logistic regression do not agree very well with the data on actual incidence of debris flows (figs. 43 and 44), so we conclude the method is not particularly useful for the case at hand.

TABLE 3.--Coefficients for logistic regression. See text for mathematical definition of regression coefficients α and β. Subscripts MAX, MIN, and R refer to maximum temperature, minimum temperature, and rainfall, respectively.

Type of weather data	Regression coefficient			
	α	β_{MAX}	β_{MIN}	β_{R}
Daily, rainfall only	4.70			-0.43
Daily, maximum temperature only	5.88	-0.09		
Daily, minimum temperature only	5.11		-0.14	
Daily, rainfall and maximum temperature	7.12	-0.14		-0.63
Three-day average, rainfall only	4.74			-0.19
Three-day average, maximum temperature only	6.01	-0.10		
Three-day average, minimum temperature only	5.29		-0.18	
Three-day average, rainfall and maximum temperature	7.72	-0.18		-0.31
Four-day average, rainfall only	4.71			-0.14
Four-day average, maximum temperature only	6.19	-0.11		
Four-day average, rainfall and maximum temperature	8.06	-0.20		-0.27
Four-day average, rainfall and maximum temperature	6.21		-0.27	-0.25
Five-day average, rainfall only	4.64			-0.10
Five-day average, maximum temperature only	6.49	-0.13		

Hypothesis for the origin of outburst floods

Outburst floods from South Tahoma Glacier involve rapid release of stored water. The total water volume (3×10^5 m^3) of the July 26, 1988 flood (fig. 14), which was probably typical, would be equivalent to an average thickness over the glacier bed (area about 2 km^2) of about 150 mm water. For comparison, water released from storage during surge 'slowdown' events at Variegated Glacier in 1983 represented average basal storage of about 50 to 100 mm (Humphrey, 1987; Humphrey and others, 1986). It may also be noteworthy that studies at glaciers comparable to South Tahoma Glacier--South Cascade Glacier (Tangborn et al., 1975), Storglaciären (Östling and Hooke, 1986) and Midtdalsbreen (Willis et al., 1991-92)--have also indicated seasonal water storage (not necessarily subglacial) of about 10^5 - 10^6 m^3.

In the Tahoma Creek debris flows, part of the total water volume must have been derived from sediments added to the triggering outburst flood as it passed through the gorge eroded into debris-rich stagnant ice, but even if 90 percent of a debris flow's water content came from such sediments, glacially derived water would represent average basal storage of 15 mm. The most plausible explanation for storage and rapid release of such a copious amount of water is the existence of a system of linked basal cavities (Fig. 46). Driedger and Fountain (1989) previously reached the same conclusion by a similar line of reasoning.

South Tahoma Glacier rests on very steep slopes (averaging 20° to 30°) and probably flows over large ledges eroded from the lavas and volcaniclastic deposits that comprise Mount Rainier. Indeed, one such ledge, several tens of meters high and formerly beneath an icefall, has been exhumed as the ice has thinned during the last decade (fig. 47). Supposing a subglacial cavity existed at the lee of such a ledge, with a cross-sectional area of 50 m^2--corresponding to a cavity 10 m in height and length, with a triangular cross-section--a total cavity length of 6 km would be required to store 3×10^5 m^3 of water. Even if the stored water volume were an order of magnitude less--corresponding to the case in which most debris-flow water comes from the sediments themselves--a 600-meter length of these enormous cavities would be required. Yet it is hard to imagine how requisite volumes of water could be stored if giant cavities do not exist. If all cavities were decimetric in scale (such as those mapped by Walder and Hallet (1979) and Hallet and Anderson (1980)), hundreds of km of linked cavities would be required to hold the stored volume of volume.

Except early in the ablation season, surficial meltwater or rainfall will rapidly reach the glacier bed via the englacial drainage system. Water at the base of an alpine glacier tends to collect in one or a few main channels incised into the ice (Shreve, 1972; Röthlisberger, 1972), but at South Tahoma Glacier, in line with previous discussion, the route from englacial conduit to trunk channel is likely to involve passage through large cavities. Flow along the linked-cavity network is regulated by the throttling effect of constrictions, or orifices, where the ice closely approaches the bed (Walder, 1986; Kamb, 1987). Based upon these concepts and results of the statistical analysis, we propose the following hypothesis: Outburst floods

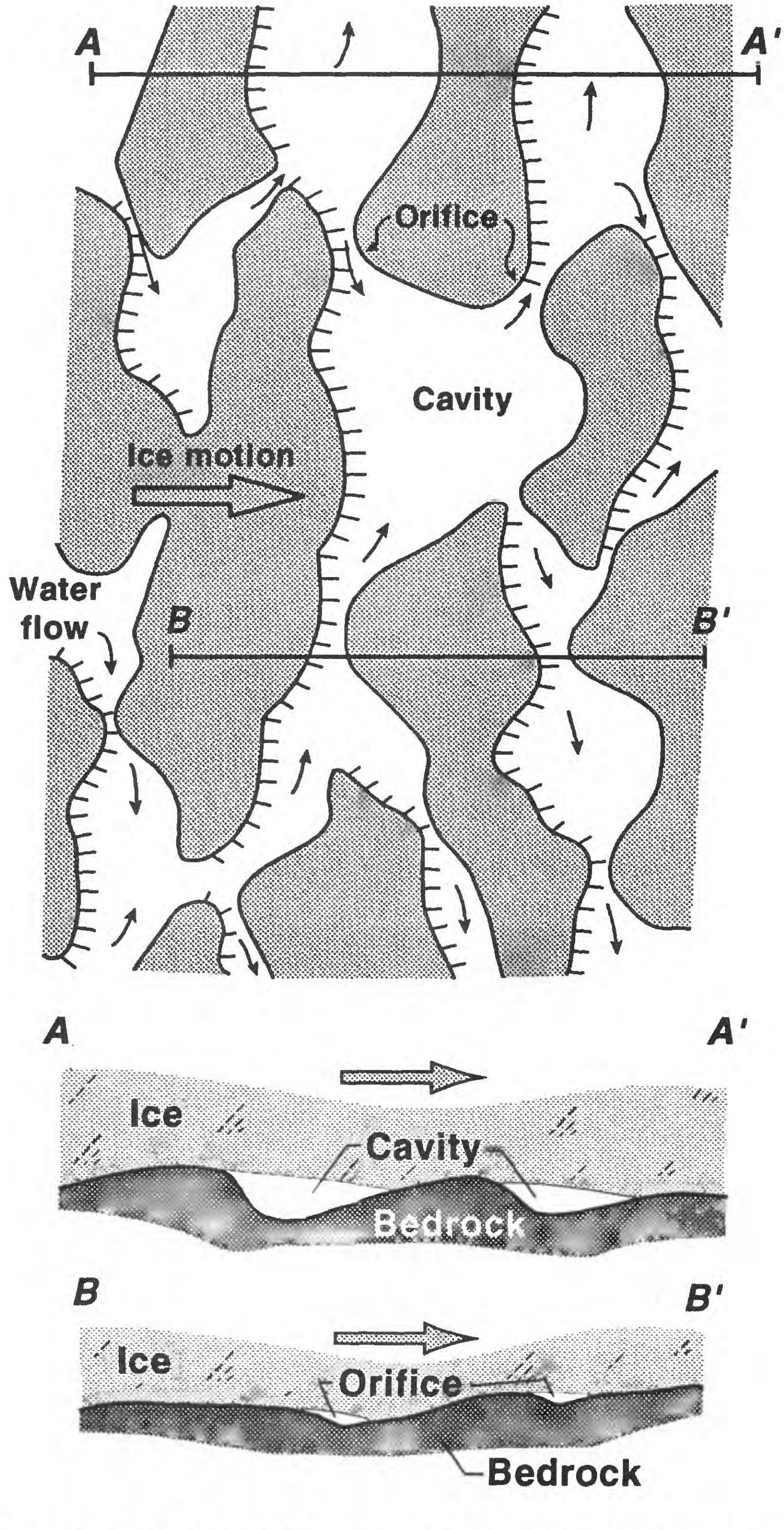


Figure 46.--Sketch of idealized glacier-bed cavities. (After B. Kamb, 1987, Journal of Geophysical Research, v. 92, no. B9, p. 9083-9100, copyright by American Geophysical Union.)

Figure 47.--View toward Glacier Island, across upper stagnant-ice zone, of rock ledges exposed by thinning of South Tahoma Glacier. Ledges first appeared about 1984. An icefall existed in this area when the glacier was larger. Photograph by L. Topinka, USGS.

from South Tahoma Glacier occur when the rate of water input to the subglacial drainage system causes subglacial water pressure to rise rapidly, destabilizing the orifices in thelinked-cavity network, in line with Kamb's (1987) analysis. The linked-cavity drainage system would then degenerate into a multiple-tunnel system that would rapidly drain stored water.

In Kamb's (1987) analysis, orifice stability is controlled by the dimensionless parameter Ξ defined by

$$\Xi = \frac{2^{1/3}}{\pi^{1/2}} \frac{(\alpha \Lambda / \omega)^{3/2}}{DM} \left(\frac{\eta}{v\sigma}\right)^{1/2} h^{7/6} \qquad (3)$$

where α is the average hydraulic gradient, approximated as the ice-surface slope; Λ is the length of orifices divided by the length of cavities; ω is the tortuosity of the water-flow path; D is a constant equal to 31 km; M is the Manning roughness of the orifices; η is the effective viscosity of the ice; v is sliding velocity; σ is effective pressure (ice-overburden pressure minus water pressure); and h is the height of the orifice. For Ξ greater than a critical value $\Xi_c \approx 1$, orifices will enlarge unstably due to transient water-pressure increases of any magnitude. For progressively smaller values of Ξ, the orifices are stable against progressively larger water-pressure transients.

To estimate a value for Ξ for the basal-cavity system of South Tahoma Glacier, we adopt the parameter values $\alpha = 0.3$, $\Lambda = 10$, $\omega = 4$, M = 0.1 s/m$^{1/3}$, η = 0.1 bar a, v = 10 m/a, and σ = 5 bars. The values for Λ, ω, M, and η follow from Kamb and should be reasonable for the South Tahoma Glacier system. The value of α applies to the active ice and is based on the 1971 USGS topographic map of the Mt Rainier West, Washington, 7.5-minute quadrangle. We have no direct measurements of sliding velocity or effective pressure at the glacier bed. Our choice of v is intuitive but plausible, based on the fact that South Tahoma Glacier has been thinning and retreating for nearly two decades, and our judgment that the glacier is sluggish. (For purposes of comparison, the average sliding speed of the nearby, larger Nisqually Glacier was about 50 m/a in 1969, while the glacier was advancing (Hodge, 1974).) The value for σ is approximately equal to the estimated average ice-overburden pressure (based on glacier area- and volume estimates by Driedger and Kennard (1986)), and thus a rough upper bound on effective pressure. With these parameter values, we find Ξ = 3.8 $h^{7/6}$, when h is given in meters. We would then require $h < 0.3$ m for the orifices to have even marginal stability. If meter-scale cavities exist, as we have previously suggested, even the orifices may have decimetric dimensions, and thus be unstable to transient increases in water pressure.

Indirect evidence possibly bearing on the size of orifices comes from a bizarre, macabre source. In December 1946, a U.S. Marine Corps airplane crashed near the head of South Tahoma Glacier, with no survivors. The wreckage was quickly buried under snow and never recovered. Deposits of the 1986 and 1987 debris flows contained many mangled bits of the aircraft, including propeller blades and pieces of sheet metal up to about 0.5 meter on a side (K.M. Scott, U.S. Geological Survey, oral communication, 1993). A plausible interpretation is that the airplane wreckage had been advected downward to the glacier bed, had melted out and accumulated in cavities, and had finally been flushed out as cavities had drained during outburst floods. The size of the metal fragments would then set a lower bound on typical orifice dimensions.

We conclude that Kamb's model of orifice instability yields quantitatively reasonable results for the case at hand. Moreover, in the context of Kamb's model, it is not surprising that the probability of an outburst flood increases as the rate of water delivery to the glacier bed increases (figs. 43 and 44). The greater the rate of water delivery, the larger must be the pressure transients, and thus the greater the likelihood that (for given Ξ) orifices in the cavity network will grow unstably.

The shortest period of time between two outburst floods from South Tahoma Glacier was about 56 hours--the interval between the floods of August 29 and August 31, 1967 (Crandell, 1971, p. 58). The floods of August 28 and August 31, 1987 were separated by only about 75 hours. In the context of the cavity model discussed above, (at least) two interpretations are possible: The linked-cavity system may rapidly reform itself after disruption leading to an outburst flood; alternatively, any individual outburst floods may represent breakdown and drainage of just part of the cavity network. We favor the second interpretation, because the volume of water released in the second of each pair of floods could not plausibly have been generated by ablation in the period between floods, even if all surface-derived meltwater had been stored subglacially. The second interpretation is also in line with observations elsewhere (for example, Fountain, 1992) that alpine glaciers may contain several distinct, internal drainage basins.

A puzzling aspect of outburst floods at South Tahoma Glacier is their probabilistic nature: few occurrences of hot weather or heavy rain do in fact coincide with outburst floods. One interpretation may be that the glacier's drainage system varies significantly with time. For example, the geometry of orifices in the cavity system might change with time, thereby affecting the value of Ξ. Another interpretation is that we simply have insufficient information about the rate of water input to the drainage system through time, as well as about the geometry of the drainage system itself, to construct a deterministic model of outburst-flood release.

Many other investigators have reported cases of glaciers that repeatedly spawn outburst floods, but these have involved drainage of either subaerial ice-dammed lakes (for example, Clarke, 1982) or subglacial lakes formed by geothermal activity (Björnsson, 1992). South Tahoma Glacier appears to be different. We are skeptical of Crandell's (1971) conclusion that geothermal activity is the proximal cause of outburst floods from South Tahoma Glacier. Crandell's argument rested on anecdotal evidence, such as observations of supposed steam plumes, gathered from a variety of observers. We believe it would be a remarkable coincidence if the statistical relation between outburst floods and meteorological variables existed independently of a causal relation between those variables and outburst floods, even though we understand the pertinent physics inexactly. Furthermore, there is no glacier-surface relief indicative of melting over a geothermal area (cf. Björnsson and Einarsson, 1990).

Other glaciers on Mount Rainier have also released outburst floods from subglacial storage, though none with nearly the frequency of South Tahoma Glacier (Driedger and Fountain, 1989). It may be that the bed geometry of South Tahoma Glacier is particularly conducive to formation of large subglacial cavities. Bed geometry must be related to the structure and erodibility of the bedrock, factors which on a stratovolcano like Mount Rainier are very heterogeneous. We note that the present phase of outburst-flood activity at South Tahoma Glacier coincides with a period of substantial ice retreat and thinning, whereas the previous phase of activity (1967 to mid-seventies) was during a period of ice advance, with the glacier considerably thicker than at present. This suggests that the propensity for outburst floods is not simply related to ice thickness.

POSSIBLE FUTURE GEOMORPHIC CHANGE

Tahoma Creek

The style and rate of possible future geomorphic change along Tahoma Creek obviously depend critically on the frequency of outburst floods, of which we cannot make any long-term predictions. If outburst floods cease, we would reasonably expect channel-wall slopes in the lower stagnant-ice zone (roughly, river kms 11.5 to 12.5) to degrade and the channel to become clogged with sediment, as in the uppermost reach of Nisqually River. Even if outburst floods continue at their present frequency, however, we expect that at some point they will no longer mobilize debris flows. Through much of the lower stagnant-ice zone, Tahoma Creek has probably eroded completely through the ice and perhaps down to bedrock. Wherever that has occurred, channel change is occurring dominantly by widening. With the passage of time, then, flood waters of a given discharge would be shallower than at present, and thus less likely to trigger slope failures by eroding the toes of unstable blocks of sediment. Ground shaking will also tend to be less intense due to a more diffuse input of acoustic energy into the ground. Thus we expect the stagnant-ice reach of Tahoma Creek to evolve to a condition in which outburst floods can pass through without transforming to debris flows.

The scenario just sketched may be a reasonable description of geomorphic change in the reach of Tahoma Creek between about river km 10.5 and river km 11.5. The glacier terminus retreated rapidly across this area between about 1910 and 1940 (Driedger, 1986), leaving stranded stagnant ice, as clearly shown in aerial photographs from 1967 (figs. 18 and 19). This reach was first incised during the 1967 outburst floods, and substantial incision occurred in connection with debris flows from 1967 through 1987. There was little change in this reach between 1988 and 1991, although in 1992, 25 years after this reach was first perturbed, bank failures and bedrock incision occurred. We suggest by analogy that the part of the stagnant-ice zone first incised in 1986--that is, upstream of about river km 11.5--will undergo a similar sort of evolution, again on a time scale of about 25 years. Any outburst floods that might occur during that period (up to about the year 2010) are likely to transform to debris flows.

Beyond the roughly 25-year period of potential debris flows, a flood hazard will exist if South Tahoma Glacier continues to spawn outburst floods. This would not constitute an unknown sort of hydrologic hazard at Mount Rainier. There are examples of outburst floods from glaciers on Mount Rainier that did not result in debris flows--most recently, at Nisqually Glacier in 1987 (Driedger and Fountain, 1989). Once a flood passed out of the constrained part of the Tahoma Creek valley and into the present depositional zone, stream avulsion would likely occur (Kellerhals and Church, 1990). Water floods would pose different hazards to NPS roads and facilities than do debris flows--erosion rather than burial by sediment would be the major concern. In this regard, it is worth noting that water floods during spring have in fact posed problems for maintenance of Westside Road since about 1990. The reason is rapid aggradation in the depositional zone of Tahoma Creek since 1986, which has reduced the stream's conveyance. As of May 1993, part of Westside Road was separated from Tahoma Creek only by a constructed levee, which has been overtopped on several occasions by flood waters.

We next consider the fate of the upper stagnant-ice area and whether it might also be a potential long-term source of sediment for debris flows. Outburst floods in 1986 and 1987 removed blocks of glacier ice and the associated cover of rock debris from this area. Scott and others (1992, p. 57) argued on sedimentological grounds that those floods had transformed to debris flows while traversing the upper stagnant-ice area. However, subsequent outburst floods, with the possible exception of the October 16, 1988 event, have apparently removed little ice or rock debris from the upper stagnant-ice zone. Rock debris in the upper stagnant-ice zone is restricted to a veneer on the glacier surface, unlike in the lower stagnant-ice zone. As the ice decays, the sediment cover slumps into meltwater channels incised into the ice and is transported by the outlet streams.

The upper stagnant-ice area could again become a short-term contributor of ice and sediment to debris flows if meltwater streams issuing from the active ice should shift position radically and incise new channels in the ice. There is no compelling glaciological reason why such shifts in outlet-stream position should happen, though they cannot be absolutely ruled out.

By 1992, the upper stagnant-ice area was almost completely detached from the higher, active part of South Tahoma Glacier. Another cycle of glacier advance and retreat comparable to the Little Ice Age advance and subsequent nineteenth- and twentieth-century retreat would probably strand new bodies of stagnant ice in the Tahoma Creek valley.

Trees killed by debris flows may constitute a continuing minor hazard. Logs and other vegetation constitute a small part of the overall volume of Tahoma Creek debris flows, but are concentrated at flow fronts, and logjams may play a role in triggering avulsion of debris flows. Dead trees may also pose a hazard when they topple.

<u>Nisqually River, Kautz Creek, and West Fork White River</u>

It is hard to identify or predict geomorphic trends for these drainages as we did for Tahoma Creek, owing to the relative infrequency of outburst floods and debris flows. In discussion above of the Nisqually River, we pointed out that the outburst flood of 1955 did transform to a debris flow, but those of 1968, 1970, and 1972 and 1987 did not, and we see no reason why comparably sized outbursts in the future would, either. Small outburst floods from Kautz Glacier and Winthrop Glacier in 1985 to 1987 did transform to debris flows (Appendix A), probably by eroding debris-rich stagnant ice stranded in the forefield of both glaciers. By analogy to the situation at Nisqually Glacier, If no further outbursts come from Kautz Glacier and Winthrop Glacier over the next 5 to 10 years, sediment sloughed from the decaying ice will choke the stream valleys, and small outburst floods thereafter are unlikely to transform to debris flows. For a very large outburst flood, however, like the 1947 Kautz Creek flow (Richardson, 1968), transformation to debris flow is probable.

SUMMARY AND CONCLUSIONS

Debris flows have been responsible for rapid geomorphic change in several glacierized drainages on Mount Rainier. All or nearly all of the best-known, most frequent debris flows--those which have moved along Tahoma Creek--began as outburst floods from South Tahoma Glacier. These floods transformed to debris flows by incorporating large blocks of sediment slumping from steep walls in a reach deeply incised into debris-rich, stagnant ice masses that are relics of glacier retreat from the mid-nineteenth century Little Ice Age maximum and the readvance of the 1960's and 1970's. Along Tahoma Creek, where 15 debris flows have passed since 1986 and at least 23 since 1967, there has been incision of several tens of meters over a reach about 2 km long since 1967, principally since 1986. At least 10^7 m^3 of sediment have been moved downstream by debris flows along Tahoma Creek. In the reach where this sediment has been deposited, unpredictable shifts in the active stream channel, along with aggradation averaging about 2 m of bouldery deposits over a reach about 4 km long, have destroyed NPS visitors' facilities and trails and repeatedly damaged the only road that provides access to the southwest part of Mount Rainier.

In the context of existing data, outburst floods from South Tahoma Glacier may be considered probabilistic phenomena. Statistical analysis shows that debris flows along Tahoma Creek have been strongly correlated with atypical weather--either unusually high temperatures or unusually heavy rain. Such conditions probably cause rapid input of water to South Tahoma Glacier, the principal source of Tahoma Creek, thereby triggering outburst floods by destabilizing the glacier's basal drainage system. There is no evidence of a geothermal cause for outburst floods at Mount Rainier.

The likelihood of debris flows along Tahoma Creek should decrease as the deeply incised reach widens by normal slope processes. We estimate that the period of debris-flow activity along Tahoma Creek that began in 1986 will last about 25 years, that is, until about the year 2010. The tendency for outburst floods to transform to debris flows should lessen with time.

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APPENDIX A: CHARACTERISTICS OF FLOODS AND DEBRIS FLOWS IN STUDIED DRAINAGES DURING THE PERIOD 1985 TO 1992

This appendix comprises brief narrative descriptions of debris flows and their deposits along Tahoma Creek, Kautz Creek, Nisqually River, and West Fork White River during the study period. Typically we were notified by NPS personnel within a day of the occurrence of any given flow, and visited the site as soon thereafter as practical to inspect deposits and changes in channel morphology. In some cases we made estimates of peak velocity and discharge of flows using the methodology of Wigmosta (1983) for estimating these variables at the site of a channel obstruction or channel bend. The crux of the method involves treating flow around a bend or past an obstruction--for example, a standing tree or a large boulder--as inviscid flow and accounting for conservation of energy. Wigmosta (1983) discussed the merits of the inviscid approximation and shows that it is reasonable. The superelevation H_s of a flow on the upstream side of an obstacle is related to the speed U of the approaching flow by $U = \sqrt{2gH_s}$, where $g = 9.8$ m/s^2 is the acceleration due to gravity. If one can identify the channel and measure its cross-sectional area A_c, peak discharge Q_p is then given by $Q_p = UA_c$, assuming that the calculated velocity equals the average velocity over the cross section. In practice, measuring H_s is difficult because of splashing that may cause mudlines on trees to be poorly defined. The method for inferring flow speed from superelevation in a channel bend involves the same physics; details are given in Wigmosta (1983).

Debris flows commonly take multiple paths where they flow in an unconfined reach of a stream valley, for example, in most of the depositional zone at Tahoma Creek, so an estimate for peak velocity or discharge may describe only one pulse of a debris flow. Finally, it is difficult to define after the fact the channel area occupied by a debris flow, especially because erosion and deposition almost certainly modify pre-existing channels. Estimates for peak discharge given below must be considered approximate, with errors as much as 50 per cent likely.

In a few cases, we were able to identify with reasonable accuracy the channel occupied by a debris flow, but could not make a peak-velocity estimate owing to lack of evidence. In such cases, we assumed that peak velocity was in the same range as estimated for other flows of comparable volume.

Jonientz-Trisler and Qamar (1989) have developed methods for identifying debris flows on seismograms recorded by earthquake seismometers at Mount Rainier and Mount Adams. Several seismometers on or near Mount Rainier, including those located at Longmire, Emerald Ridge, and Fremont Peak, have recorded signals attributable to debris flows, and we cite seismic evidence for debris-flow occurrence where appropriate. Seismograms were interpreted by C. Jonientz-Trisler of the University of Washington unless otherwise stated.

At Tahoma Creek, flow stage following a debris flow generally rose by 0.5 m or less at the Nisqually-Longmire Road bridge (river km 1). Flows in this reach were watery and carried only sandy and silty sediment.

Debris flow of July 18, 1985 at Kautz Creek--Weather was hot and dry, with no precipitation since the previous month. The seismogram recorded at Longmire showed evidence of debris-flow movement between 3:53 p.m. and 4:04 p.m. Because of the relative remoteness of the region affected by this debris flow, its deposits were not noted for nearly a week. Those deposits were found below about river km 7.5, approximately 4 km downstream of the glacier terminus, and buried the Wonderland Trail bridge at river km 7.0 to a thickness greater than 1 m. At the highway bridge (river km 1.0), mud lines showed that the water level had increased about 0.3 m. The magnitude of this debris flow seems to have been similar to the subsequent one of September 4, 1986, for which K.M. Scott of the USGS estimated $Q_p \approx 100\ \mathrm{m^3/s}$.

Debris flow of September 4, 1986 at Kautz Creek--Weather was hot and dry. Seismic records indicate debris-flow movement between 6:55 and 7:01 p.m. and again between 7:29 and 8:18 p.m. The deposit thickness was 1 to 2 m near river km 7.0. K.M. Scott, USGS, estimated $Q_p \approx 100\ \mathrm{m^3/s}$ in this reach. This estimate probably pertains to the second debris-flow pulse.

Outburst flood of June 22, 1987 at Nisqually River--Weather was warm and dry. At 7:00 a.m., C.L. Driedger saw water emerging from the base of an icefall and flowing over the surface of Nisqually Glacier. The water poured off the terminus to the river bed below. No debris flow formed, nor was any notable geomorphic change produced along the Nisqually River. Water continued to flow over the glacier surface at a modest rate for approximately 24 hours. Andrew Fountain, USGS, made a field inspection of the channel cut by the superglacial flow and, using channel dimensions and an estimated roughness coefficient, estimated $Q_p > 2\ \mathrm{m^3/s}$. This value applies to the superglacial flow only.

Debris flow of August 9, 1987 at West Fork White River--Weather was hot and dry. The seismogram recorded at Fremont Peak indicates that this debris flow, which moved along an unnamed tributary of the West Fork White River, occurred between 10:45 and 10:48 p.m. On the basis of the distribution of deposits, C.L. Driedger and P. Pringle concluded that the flow was confined between the lower slopes of Mineral Mountain and the west margin of Winthrop Glacier. Levees 4 m or greater in height were deposited in the vicinity of river km 5.0. At the Wonderland Trail crossing near river km 3.2, thickness of debris-flow deposits was $\geq 3\ \mathrm{m}$. Near river km 3.0, the debris flow breached its levees and flowed across the channel of the West Fork White River. Driedger and Pringle estimated $Q_p \approx 70\ \mathrm{m^3/s}$ at river km 3.2 and 270 m^3/s at river km 3.7. There are many ponds on the surface of stagnant ice at Winthrop Glacier, and it is possible that this debris flow was triggered by drainage of one of them, although there is no firm evidence of this.

Debris flow of October 26, 1986 at Tahoma Creek--Weather was cool and rainy. The Longmire seismogram recorded debris-flow movement between 1:54 and 2:12 p.m. This debris flow inundated the former Tahoma Creek picnic area near river km 7.5 and left bouldery deposits in the river channel in the reach between approximately river km 9.0 and river km 5.0. This was the first episode of substantial incision of stagnant, debris-rich ice between about river km 12.0 and river km 12.5. K.M. Scott estimated $Q_p \approx 10^3$ m^3/s at the Wonderland Trail suspension bridge, near river km 10.4.

Debris flow of June 29, 1987 at Tahoma Creek--The weather was warm and dry. The Longmire seismometer recorded debris-flow movement between 2:08 and 2:30 p.m. Two visitors to the Park witnessed this debris flow from the Wonderland Trail suspension bridge at river km 10.4. They reported that the debris flow was preceded by a strong down-valley wind and loud rumbling. Thickness of bouldery deposits near the former Tahoma Creek picnic area (river km 7.5) exceeded 1 m. Levees 3 to 4 m in height were deposited between river km 6.5 and river km 7.3. K.M. Scott, USGS, estimated $Q_p \approx 10^3$ m^3/s.

Debris flow of August 28, 1987 at Tahoma Creek--The weather was warm and dry. The Longmire seismometer recorded debris-flow movement between 5:04 and 5:13 p.m. Field investigation was limited to views at river km 5.6. At this location, the debris flow traveled in the channel established by the debris flow of June 29, 1987 and did not inundate forested areas, as had previous flows. We estimated $Q_p \approx 20$ m^3/s on the basis of channel dimensions and superelevation on boulders.

Debris flow of August 31, 1987 at Tahoma Creek--Weather was warm and dry. The Longmire seismometer recorded debris-flow movement between 8:21 and 8:37 p.m. Field inspection by C.L. Driedger and C.H. Swift, USGS, revealed that this debris flow had breached older debris-flow levees near river km 6.5, then flowed through a forested area toward the west. Near the Wonderland Trail suspension bridge (river km 10.4), $U \approx 9$ m/s and $Q_p \approx 760$ m^3/s, on the basis of superelevation in a channel bend and channel dimensions.

Debris flow of September 23, 1987 at Tahoma Creek--The weather was warm and dry. The Longmire seismometer recorded debris-flow movement between about 6:30 p.m. and 7:00 p.m. On the basis of superelevation on trees, C.L. Driedger and C.H. Swift, USGS, estimated $U \approx 2$ m/s in the former picnic area at river km 7.4. Near the suspension bridge at river km 10.5, estimates of $U \approx 15$ m/s and $Q_p \approx 1700$ m^3/s were made on the basis of superelevation and channel dimensions. This debris flow devastated what had remained of the former picnic area.

Debris flow of July 14, 1988 at Tahoma Creek--Weather was cool and drizzly. The Longmire seismometer recorded debris-flow movement between 1:46 and 2:00 p.m. At approximately river km 5.6, the debris flow overtopped the Westside Road and left bouldery deposits of thickness 0.5 to 1.0 m for a distance of about 150 m, stranding 22 people and several automobiles, according to NPS staff. Part of the debris flow entered Fish Creek. Turbid water that followed the debris flow eroded a trench 1 to 2 m deep near the center of the road. No appreciable rise of water was noted at the highway bridge. C.L. Driedger and C.H. Swift, USGS, estimated $Q_p \approx 1300$ m^3/s near river km 6.5.

Debris flow of July 26, 1988 at Tahoma Creek--Weather was warm and dry. The Longmire seismometer recorded debris-flow movement between 3:48 and 4:01 p.m. This flow was witnessed by G.G. Parker and C.H. Swift, USGS, from a vantage point near river km 8.0. Swift's estimated hydrograph is presented in the main text as fig. 17. Estimated peak velocity and peak discharge were 5 m/s and 540 m^3/s, respectively. Distinct levees were deposited in the vicinity of river km 7.0.

Debris flows of October 16, 1988 at Tahoma Creek--Weather was cool and very rainy. The seismogram from Longmire showed debris-flow signals between 5:30 a.m. and 6:02 a.m. and again between 2:53 p.m. and 3:43 p.m. Park ranger J. Wilcox observed one of these flows. Deposits locally exceeded 8 m in thickness near river km 7.7. Mud lines showed there had been a rise in stage of about 5 m at river km 6.5. On the basis of superelevation on trees, J.J. Major and C.L. Driedger, USGS, estimated $Q_p \approx 600$ m^3/s near river km 6. Westside Road was seriously damaged. At the highway bridge, water level rose about 1 m; after flow had returned to the ambient level, the stream bed was seen to be littered with tree trunks, causing concern about bridge safety. Sunshine Point Campground near the confluence with the Nisqually River was closed because of potential flood hazard.

Debris flow of September 23, 1989 at Tahoma Creek--Weather was hot and dry. Park ranger R. Kirschner observed this flow in a confined reach at about river km 9.5. The flow there was about 2 m deep. Kirschner noted sloughing of sediment from the banks. Our later inspection suggested this was a relatively small debris flow, as no new bouldery deposits were noted near the former picnic area, although there were muddy coatings there on older deposits. Estimated peak velocity from superelevation on boulders was $U \approx 4$ m/s. Estimated peak discharge using this value of U ranged from 30 to 76 m^3/s. It is likely this debris flow would have gone unnoticed if not for the serendipitous observations by Kirschner and associated ground shaking recorded by the Emerald Ridge seismometer.

Debris flow of November 9, 1989 at Tahoma Creek--Weather was cool and very rainy. The Longmire seismometer recorded debris-flow activity between 5:00 and 6:02 a.m. Field inspection showed extensive deposition and morphological change in the stream bed between river km 6.0 and river km 9.0. On the basis of superelevation on boulders, we estimated $Q_p \approx 60$ m^3/s in one well-defined channel at river km 7.

Debris flow of August 4, 1990 at Tahoma Creek--Weather was hot and dry. This flow was first detected by S. Malone at the University of Washington, who happened to identify its seismic trace on the Emerald Ridge seismogram as the flow was in progress. Field inspection showed no new bouldery deposits as far downstream as the former picnic area (river km 7.5), although we did find mud marks on trees. At about river km 7.7, we used superelevation on boulders within older deposits to estimate $U = 2.7$ m/s and $Q_p \approx 150$ m^3/s. At about river km 8, new debris-flow lobes had engulfed trees and left distinct superelevation marks. We estimated $U = 3$ m^3/s and $Q_p \approx 180$ m^3/s at that point.

Debris flow of October 3, 1990 at Tahoma Creek--Weather was cool with heavy rainfall. The Emerald Ridge seismogram showed ten debris-flow pulses, each with a duration of 10 to 32 minutes, over an 8.5 hour period. Our general impression of the deposits was that there had been numerous flows, with the stream channel repeatedly blocked by debris-flow deposits, followed by avulsion. We found no distinct levees. Several steep snouts of deposits, presumably reflecting places where flows had stopped, contained abundant logs. We estimated the total volume of bouldery material deposited as approximately 1 to 2×10^5 m^3. We made three estimates of peak discharge: 70 m^3/s at river km 7.6, 130 m^3/s at river km 8.5, and 500 m^3/s at river km 8.6. For the first and last of these estimates, we estimated velocity from superelevation on trees; for the second estimate, we assumed the same velocity as at the first site. These estimates probably referred to discrete debris-flow pulses.

Debris flow of November 5, 1991 at Tahoma Creek--Weather was cool and very rainy. The flow was detected by an NPS road crew working on the Westside Road. The Emerald Ridge seismogram, which was hard to interpret owing to wind-generated noise, suggested the flow lasted about an hour. Field inspection showed a deep gully cut into the Westside Road slightly above the Fish Creek confluence (river km 5). This was also the downstream end of bouldery deposits left by this flow. We found one location, at about river km 9, where we could infer peak discharge from superelevation on trees. We estimated $U \approx 6$ m/s, $Q_p \approx 600$ m^3/s, and the total volume of coarse deposits as about 10^5 m^3.

Debris flow of September 8, 1992 at Tahoma Creek--Weather was cool and rainy. The flow was heard but not seen by NPS personnel. Field inspection showed bouldery deposits on the Westside Road at the Fish Creek confluence; those deposits appeared to have been subsequently eroded by a watery flow. The debris flow had overtopped a levee alongside the road constructed by NPS personnel after the debris flow of November 5, 1991. Near the former picnic area, at river km 7.5, there was clear evidence that the flow (or pulses thereof) had moved through at least two different channels. We estimated peak discharge in one of those channels at about 300 m^3/s. Farther upstream, new deposits comprised 3 or 4 layers, each layer consisting of sandy material overlying bouldery material, perhaps indicative of pulses within the debris flow (fig. 48).

Debris flow of September 20, 1992 at Tahoma Creek--Weather was cool and rainy. We were not notified about this flow until September 25, and did not inspect the deposits until a week thereafter. This flow seemed about as large as the flow of September 8, 1992. It had again overtopped the levee alongside the Westside Road slightly upstream of the Fish Creek confluence at river km 5. We did not find any places where we could make reliable estimates of peak velocity or discharge.

Looking upstream from the suspension bridge, we saw that the waterfall just upstream of the confluence with the Tahoma Glacier tributary, at river km 10.6, had retreated upstream. At the former waterfall site, the stream was incised in a notch in bedrock about 15 m wide and equally deep. There had been substantial bank failure along the southeast side of Tahoma Creek between the suspension bridge and the confluence with the Tahoma Glacier tributary. Because we had not visited the bridge following the September 8, 1992 flow, we are uncertain exactly when the changes upstream of the bridge occurred, although they must have occurred in association with at least one of the two September flows.

Figure 48.--Deposits of September 8, 1992 debris flow near river km 9.0. Note alternating layers of bouldery and boulder-free sediment, perhaps indicative of debris-flow pulses. The distance between the two strata indicated by arrows is about 0.5 meters.

APPENDIX B: DATA ON STAGE, CONDUCTIVITY AND TURBIDITY

Other investigators (for example, Humphrey (1987)) have shown that measurements of electrical conductivity and turbidity in glacial melt streams may be useful for inferring characteristics of the basal drainage system. Accordingly, data on stream stage, electrical conductivity and turbidity at Kautz Creek, Tahoma Creek and Nisqually River were collected during 1987. Table 4 lists the variables measured at the various sites, which are indicated on figs. 4 and 6 of the main text. Two gaging stations were installed on Nisqually River, two on Kautz Creek, and one on Tahoma Creek, to monitor flow stage. Either electrical conductivity or turbidity of the stream water was measured at three of the five gaging stations. Electrical conductivity and turbidity were measured with probes submerged in the stream. The turbidity sensor was not calibrated relative to absolute values of sediment concentration and thus measured only relative change in turbidity. Meteorological data (rainfall or temperature) were also collected at three of the stations. All data were collected at 15-minute intervals. Data were either logged on site or telemetered to a USGS office in Tacoma, Washington.

At the upstream stations on Kautz Creek and Nisqually River (12081910 and 12081590, respectively), stage was monitored using pressure transducers that measured the pressure of nitrogen gas filling a tube submerged in the stream. This afforded safety to the transducers by maintaining them high above potential flood levels. At the lower stations on Kautz Creek and Nisqually River (12081910 and 12081595, respectively), stage was measured by submerged pressure transducers. At station 12081990 on Tahoma Creek, stage was measured with a sonic rangefinder.

Upstream stations along Kautz Creek and Nisqually River were placed as close to the glacier terminus as practical to minimize effects of channel storage and influences of non-glacial runoff, yet far enough from the glacier to avoid hazards of potential rock- or ice avalanches. The downstream stations on these streams, as well as the Tahoma Creek gaging station, were located near highway bridges and down-valley of the expected depositional zones of potential debris flows.

The electrical conductivity of stream water depends upon concentration of solutes, which itself depends upon water temperature and, because of dissolution kinetics, travel time between water source and measurement point. Fenn (1987) discussed this with particular reference to glacially derived streams. In the case of alpine streams such as those monitored, conductivity may be altered by change in the relative contributions of snow melt, glacial runoff, ground water and precipitation. Turbidity can sometimes serve as a proxy for electrical conductivity (Humphrey, 1987), although we did not in this study make the calibrations required to do so.

TABLE 4.--Types of data collected at stream-gaging sites.

Site	River stage	Electrical conductivity	Turbidity	Precipitation	Air temperature
Nisqually River station 12081590	X			X	
Nisqually River station 12081595	X	X			
Kautz Creek station 12081900	X		X	X	
Kautz Creek station 12081910	X	X			X
Tahoma Creek station 12081990	X				

All of the monitored streams are braided, gravel-bed streams that erode their beds and shift their courses unpredictably, so determining stage/discharge relations was impractical. We did use the salt-dilution technique (Rantz and others, 1982) to make point measurements of discharge at station 12081595 (Nisqually River) and station 12081990 (Tahoma Creek) during 1987 and again on Tahoma Creek in 1989. As both of these streams are fed primarily by glacial runoff, discharge changes substantially during the course of a day, particularly on a sunny day (Fahnestock, 1963; Röthlisberger and Lang, 1987). Both streams showed discharge of about 2 to 3 m^3/s during rainless periods.

Nisqually River

Measurements were made at gaging station 12081590 from July 19, 1987 to November 18, 1987. Stage varied by about 1.2 m (fig. 49). The diurnal variation was as much as 0.7 m on a few days during July and August. Diurnal variation noticeably decreased after about mid-October, presumably because of decreased runoff from melting of snow and ice. Storms in mid-August, mid-September and late October were accompanied by decrease in stage. Presumably, decreased melt-water runoff caused by decreased insolation more than offset the input of storm-water runoff to the stream. In contrast, two storms that occurred in November, by which time ablation of snow and ice at high elevations had probably ceased, caused immediate, distinct rises in stage.

Instrumentation was installed slightly upstream of the highway bridge at gaging station 12081595 on September 30, 1987 and maintained until November 18, 1987. Stage varied by about 0.5 m during the period of record. The maximum diurnal variation was about 0.3 m (fig. 50). An average conductivity of 0.8 microsiemens (μS) was measured with variations of about 0.1 μS. Conductivity generally correlated positively with discharge. A possible interpretation (compare Humphrey, 1987) is that melt water moving through the subglacial drainage system has a relatively higher concentration of dissolved solutes that other waters entering the stream.

Kautz Creek

Stage varied by about 0.1 m at gaging station 12081900, which operated from July 24, 1987 to November 24, 1987 (fig. 51). Diurnal variation was commonly 0.03 m or more from July through September, but only about 0.01 m or less in late October and November. Runoff was affected by storms in a manner similar to that observed on the Nisqually River and described above. Turbidity generally did not vary greatly, although there were noticeable increases correlated with minor storms in late September and mid-October. Turbidity also rose noticeably during about the last week of data collection, perhaps correlated with several storms during that period. Turbidity tended to vary inversely with stage, but this association was not constant through the record. A possible interpretation is that because of dilution, turbidity tended to fall as stage (thus, in general, discharge) increased. This effect might be partly offset by stream-bank erosion. The turbidity indicator was buried and destroyed during the rainstorm that began in the second week of November.

An air-temperature sensor was installed at station 12081910 on August 26, 1987. Equipment to measure stage and conductivity were installed on September 23, 1987. The station was maintained until November 23, 1987. During this period, stage varied by about 0.35 m with a maximum diurnal variation of about 0.15 m (fig. 52). Electrical conductivity measured at this station ranged from about 0.7 to 0.8 μS with diurnal variation of about 0.1 μS. Conductivity generally correlated positively with variations in discharge.

Tahoma Creek

Gaging station 12081990 was extremely difficult to maintain owing to the highly mobile stream bed, which farther upstream had been extensively disturbed by passage of debris flows. The stream was not instrumented until autumn of 1987, after three debris flows had occurred that summer. Stage was measured between from October 24, 1987 to December 10, 1987. Stage ranged from about 1.6 to 1.9 m and experienced distinct diurnal fluctuations (fig. 53).

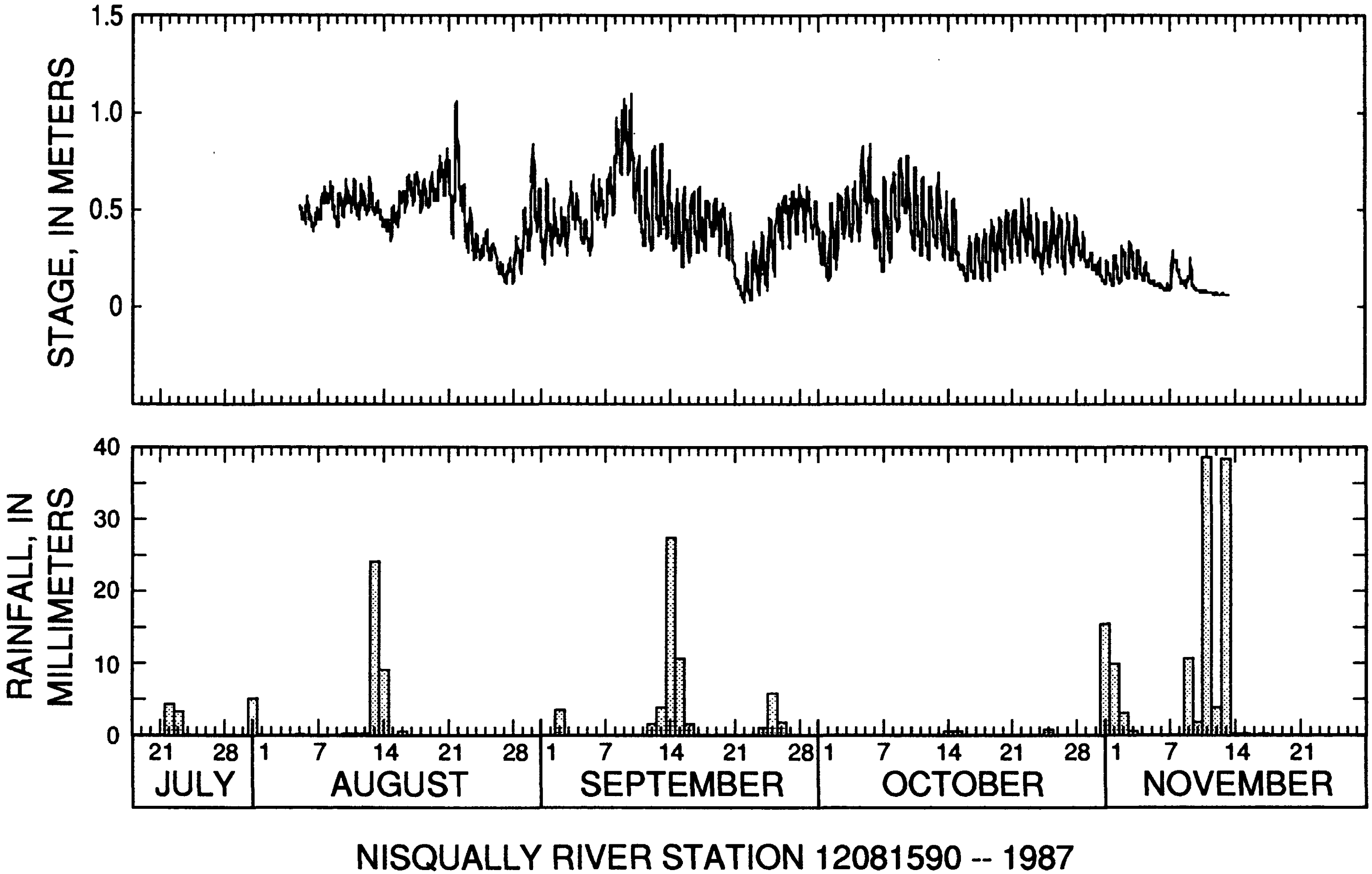

Figure 49.--Stream stage and rainfall measured at station 12081590, Nisqually River, during 1987.

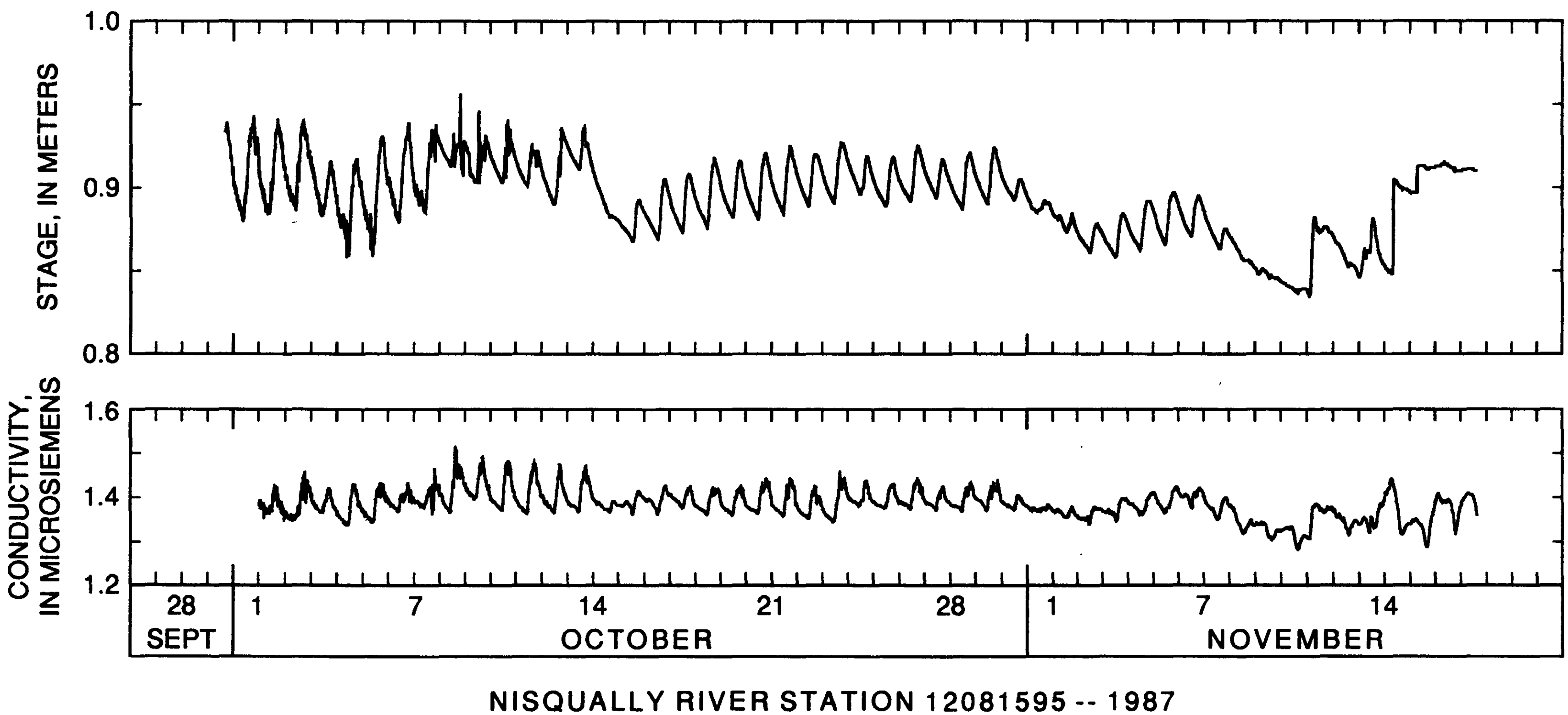

Figure 50.--Stream stage and electrical conductivity measured at station 12081595, Nisqually River, during 1987.

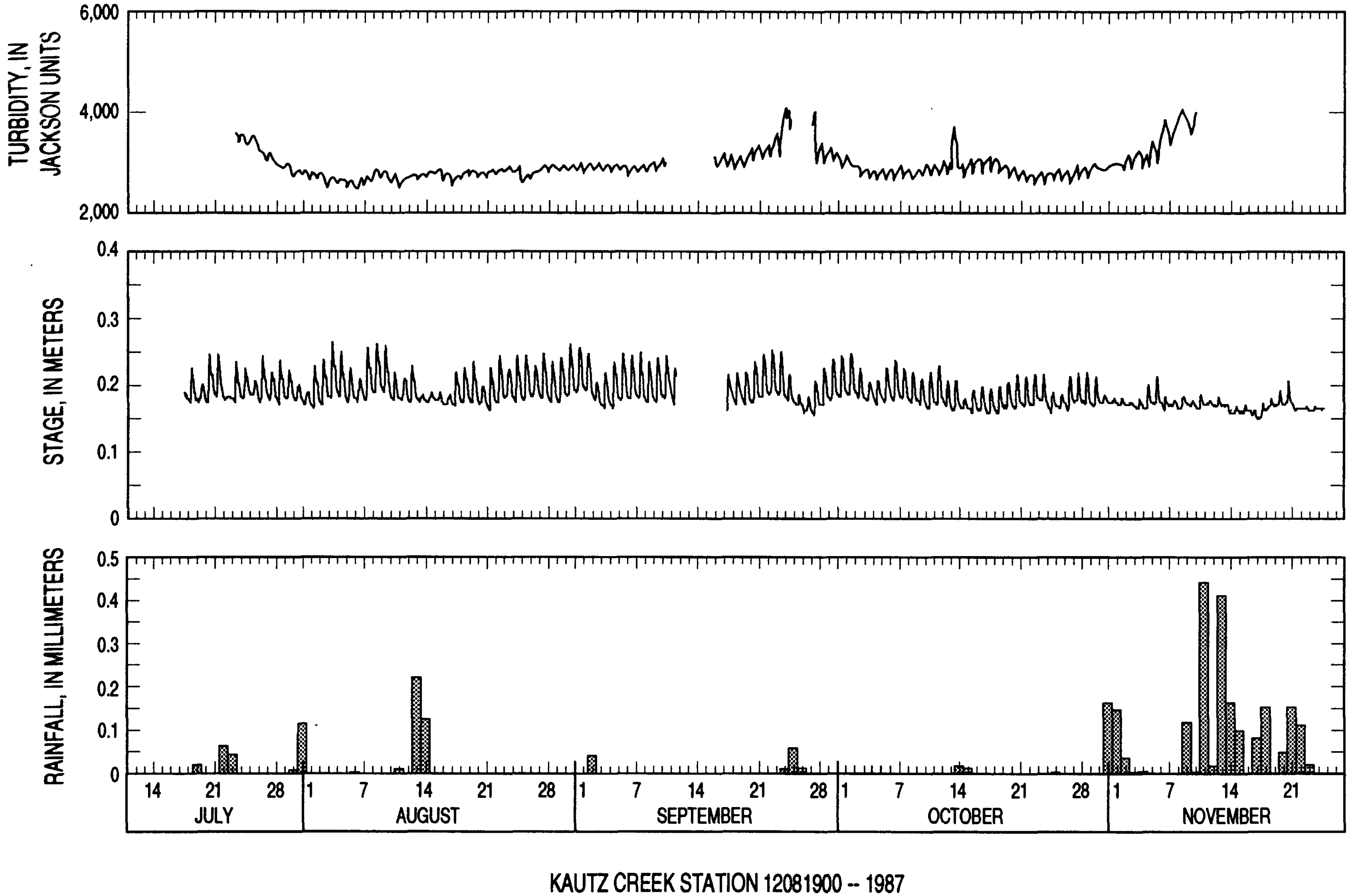

Figure 51.--Turbidity, stage and rainfall measured at station 12081900, Kautz Creek, during 1987.

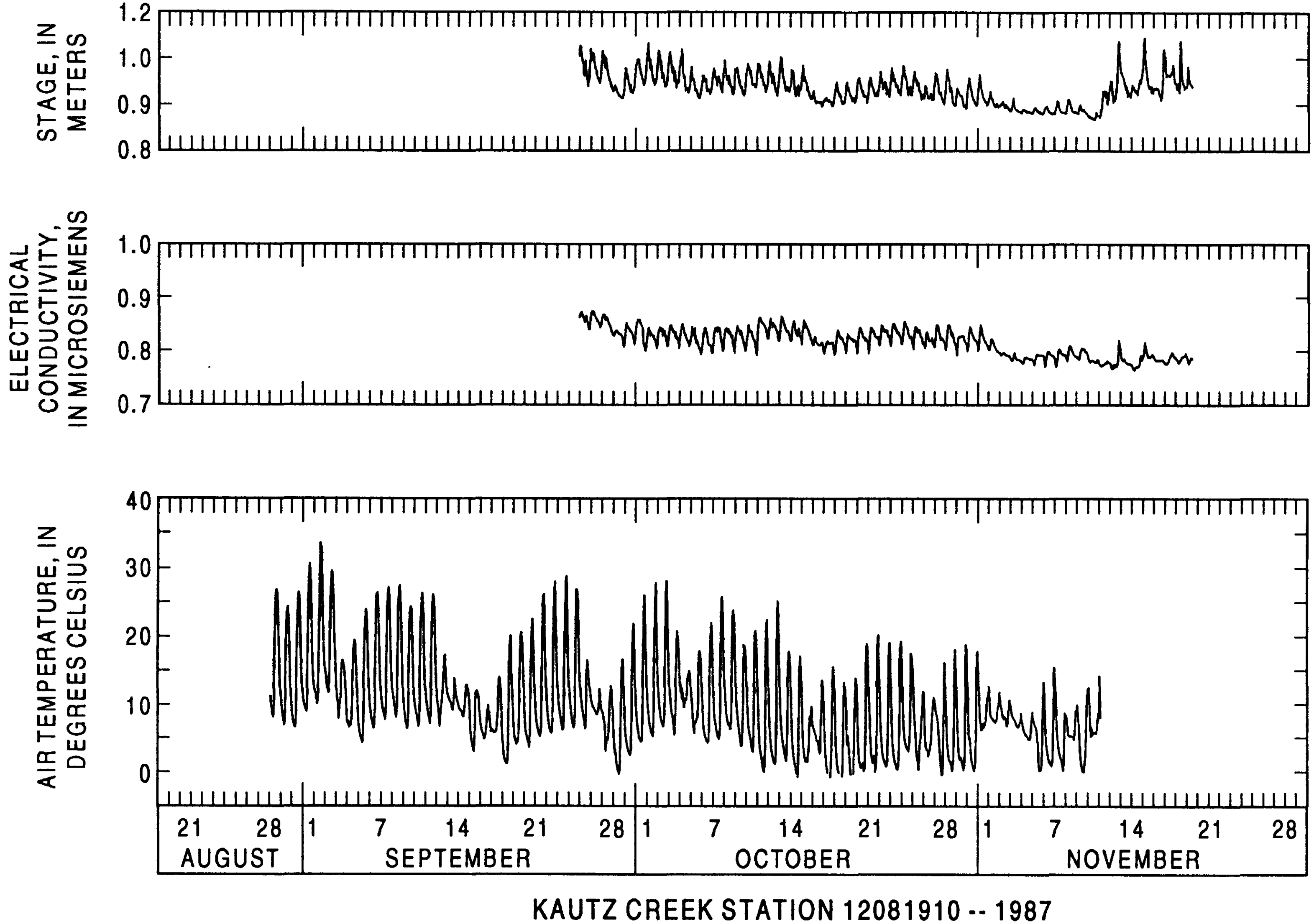

Figure 52.--Stream stage, electrical conductivity and air temperature measured at station 12081910, Kautz Creek, during 1987.

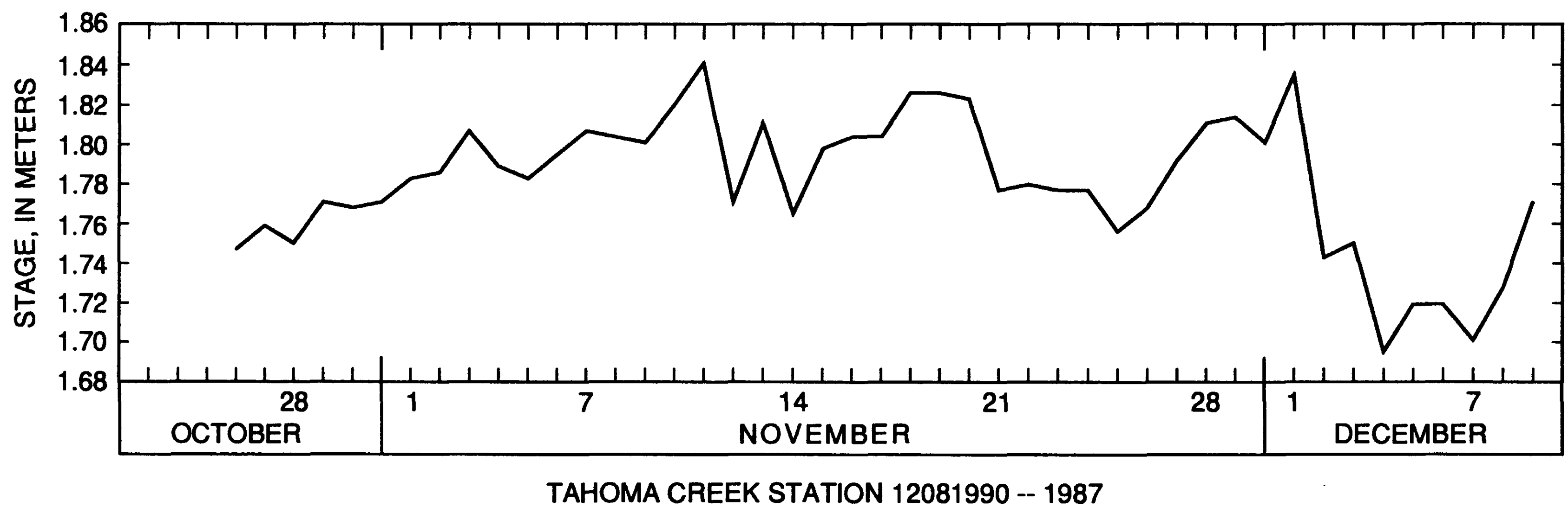

Figure 53.--Stream stage measured at station 12081990, Tahoma Creek, during 1987.