GLACIER DAMMED LAKES AND OUTBURST FLOODS IN ALASKA

BY

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INTRODUCTION

Glaciers in Alaska cover an area of about 73,800 square kilometers (28,500 square miles). They are most highly concentrated along the Pacific Coast and in the south-central part of the State. Many of these glaciers, as elsewhere in the world, flow across the mouths of adjoining valleys and cause lakes to form behind the ice streams. These glacier ice dams are subject to repeated failure. Because most Alaskan communities and transportation routes are situated along rivers which flow from glaciers the hazards presented by glacier dammed lakes are serious. The damage by floods from these lakes will increase if people encroach into areas where flooding occurs.

Glacier dammed lakes in south-central and southeastern Alaska and in adjacent Canada which drain into rivers entering Alaska are included in this study. Such lakes are numerous in this area; 750 glacier dammed lakes have been plotted on the maps on sheets 1 and 2. The number and size of individual lakes vary enormously during the seasons and from year to year; the total number of lakes plotted provides an indication of their abundance.

Not included in this report are the few, very small lakes dammed by glaciers that are widely scattered in the Brooks Range, Alaska Peninsula, Kodiak Island, and Aleutian Islands.

The major hazard presented by glacier dammed lakes is catastrophic flooding which occurs when the ice dams fail. In many places flooding occurs annually; there are many exceptions and the situations change rapidly from one year to the next.

It should be noted that large quantities of water can also be stored in or under glaciers and may create serious floods even though no surface lake is visible. Such catastrophic floods have occurred in Iceland so frequently (Thorarinsson, 1953) that the Icelandic term "jökulhlaup" is now used internationally to describe them. In the State of Washington floods of this nature have been observed from at least four glaciers (Richardson, 1968). Thus, glaciers with no visible lakes may present unusual flood hazards. However, one cannot identify from aerial photographs or maps those glaciers which are likely to produce large jökulhlaups except to note a common association of glacier outburst floods with glacier-clad volcanoes. Any glacier may produce an outburst flood, but only visible glacier dammed lakes and glaciers on volcanoes are shown in this report. The largest glacier outburst floods in Alaska are from the release of glacier dammed lakes.

The purpose of this report is to present an up-to-date assessment of the hazardous glacier outburst floods in Alaska by mapping the present extent of glaciers, the location of glacier dammed lakes and glacier-clad volcanoes, presenting the recent history of several prominent glacier dammed lakes, and delineating areas where outburst flooding may be expected. Avoiding particularly hazardous situations is advised and recommendations are made for monitoring a few lakes which cause very large or potentially damaging floods.

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HOW THE DATA WERE COMPILED

Base maps showing the glaciers were compiled from United States and Canadian topographic maps, scale 1:250,000 reduced to 1:1,000,000. These were extensively revised and brought up to date by checking more than 15,000 aerial photographs of glaciers taken by Post between 1960 and 1970. Eight hundred of these photographs as well as aerial photographs taken by A.W. Balvin, 1963; Bradford Washburn 1934, 1942; U.S. Air Force 1942–48; U.S. Navy 1929, 1948, 1957; and U.S. Geological Survey 1950–62; showing the various lakes and lake sites, were compared with lakes and closed depressions near glaciers shown on the largest scale topographic maps available for each area. Observations of glacier dammed lakes recorded by other investigators as well as on-site investigation of several lakes aided in the interpretation of the maps and photographs.

Innumerable tiny lakes smaller than 0.1 square kilometer (0.04 square mile), which occur on and beside the glaciers, were not included in this inventory. Hundreds of small lakes situated in potholes on stagnant, moraine-covered ice are also not shown. All other glacier dammed basins larger than 0.1 square kilometer (0.04 square mile) which show evidence of having contained lakes in the past decade are plotted on the maps on sheets 1 and 2. Evidence for these lakes includes: lack of vegetation, fresh shoreline erosion, stranded icebergs in recently drained basins, and crevassing related to floating of ice adjacent to ice marginal lakes or above subglacial lakes. Locations where potential lakes may develop if recent changes in glaciers continue were evaluated and are shown on the maps, as are the more noteworthy of many former lakes which have existed within the past 250 years.

The downstream areas where floods have recently occurred or are considered in serious danger of future floods are also shown on the maps. As relatively little data on inundation areas are available, many flood plain areas shown are interpreted to be hazardous simply due to the presence of glacier dammed lakes. The Snow River inundation area (map, sheet 2) was mapped during an outburst flood in 1970. All other inundation areas are the active flood plain areas interpreted from topographic maps and aerial photographs.

In the table (sheet 1) are listed 32 of the largest, most hazardous or unique glacier dammed lake situations. Included are all of the lakes for which historical records or detailed flood data are available.

THE FORMATION OF GLACIER DAMMED LAKES

Glacier dammed lakes form in a number of different situations. The largest lakes, which present the greatest hazards, occur in ice free tributary valleys blocked off by active valley glaciers. Most common are small lakes situated in alcoves and niches in the valley walls along the margins of glaciers and in depressions formed where tributary valley glaciers join. A few lakes are located slightly above the regional firn line; the large majority occur along the lower reaches of glaciers.

No attempt is made here to classify glacier dammed lakes as to manner of formation such as by active or stagnant ice, or by advancing or retreating glaciers. Glacier dammed lakes can be formed, change size, or be destroyed in so many ways in various geomorphic settings that a complete classification would be both cumbersome and of very little practical value.

Once a depression is closed off by a glacier it begins to fill with meltwater and rain runoff from the surrounding basin. The resulting lake continues to fill until the water overflows a bedrock saddle or initiates a self dumping process at the ice dam. Filling continues at a reduced rate during the winter by water draining from the porous old snow in the higher areas of nearby glaciers. Winter snowfall also adds to the lake height.

Most large ice-dammed lakes fill until they reach depths where the ice dam becomes unstable. Summit Lake, British Columbia (No. 1) released in 1961 and 1965 when the water depth equaled 0.82 of the ice thickness (computed from data reported by Mathews, 1965). The maximum possible depth is that necessary to float the dam, which is approximately 0.9 of the ice thickness. The lake in the Snow River basin (No. 26) in September 1970 rose to a depth of 0.9 of the ice dam level before drainage began.

HOW GLACIER DAMMED LAKES RELEASE

The release of glacier dammed lakes may be initiated by the formation of a channel under, through, or over the ice in one or more of the following ways:

1. Slow plastic yielding of the ice due to hydrostatic pressure differences between the lake and the adjacent, less dense ice (Glen, 1954).
2. Raising of the ice dam by floating (Thorarinsson, 1939).
3. Crack progression under combined shear stress due to glacier flow and high hydrostatic pressure (Nichols and Miller, 1952).
4. Drainage through small, preexisting channels at the ice-rock interface or between crystals in the ice.
5. Water overflowing the ice dam, generally along the margin (Liestøl, 1956).
6. Subglacial melting by volcanic heat (Tryggvason, 1960).
7. Weakening of the dam by earthquakes (Tryggvason, 1960).

Once a leak is established the initial opening can be expanded rapidly by melting (Liestøl, 1956). The lake water is usually slightly above the melting temperature (Gilbert, 1969); in addition heat is supplied by conversion of potential energy of the water into heat energy during its passage through the ice. The rate of increase of tunnel cross-section area due to melting must be related to the water discharge and the heat available. The size of the passage at any time is therefore related to the volume of water which has already passed through it. In addition to melting, mechanical scouring strips partially melted ice crystals from the tunnel walls increasing the tunnel diameter. In the early stages of outbreak the water discharge increases slowly at first and then faster and faster—in at least one case, Lake George in Alaska, the increase followed an exponential law (Meier, 1960). This accelerating rate of increase occurs until the discharge reaches extremely high values. As the lake drains the lowering of the lake then reduces the water and energy available, and the discharge decreases abruptly. Because plastic flow of the ice is usually too slow to close the opening as rapidly as the water pressure is reduced, the channel remains open long enough for most reservoirs to drain completely. The time required for a lake to release varies from a few hours to several days. So many factors combine to influence the intensity and duration of flooding that quantitative generalizations are not possible with present data.

Occasionally, at least, a lake may drain with no flood resulting (Lindsay, 1966). Data from lakes where streamflow records exist indicate that the lakes usually drain rapidly enough to present flood hazards at least a few kilometers downstream from the glacier terminus. For example, small lakes on Martin River Glacier were observed by Tuthill and Laird (1966, p. 21–22) to fill and release in the summer of 1964, causing local flooding on the outwash plain at the head of Lake Charlotte near the Bering River. Even where there is no evidence of past flooding, one should assume that any glacier dammed lake may drain abruptly and rapidly with little or no advance warning.

CHARACERISTICS OF FLOODS FROM GLACIER DAMMED LAKE OUTBURSTS

A large majority of the smaller lakes shown on the maps fill and empty one or more times each year. A tiny glacier dammed lake at Gulkana Glacier in the Alaska Range (map, sheet 2) filled and drained at three-day intervals during the 1970 summer (gaging station 15-4780.4). Two small lakes adjacent to Lemon Creek Glacier (map, sheet 1) near Juneau drained several times during the summer of 1967 (C. Zenone, oral commun., 1968). Aerial photographs taken each year show that most of the small lakes and many of the larger ones have drained by late August. Seasonal cycles in subglacial water pressure may be present (Mathews, 1964) and may affect the dumping cycle.

Although most small glacier lakes appear to have drained by late summer, the time of glacier lake release is not related to weather patterns in any simple way. Regardless of the time of year, glacier dammed lakes release whenever they fill to critical levels. Several of the large lakes drain annually (see photograph of Tulsequah Lake, sheet 3) and others drain only once each 2 to 4 years (see photographs of Summit and Blockade Lakes, sheet 3). The longer time period occurs where the lake basins are so large that they require several years for filling.

Although most glacier dammed lakes are not large, the rapid draining which can take place may result in extremely large floods. For example, Summit Lake, British Columbia (No. 1) dammed by Salmon Glacier has a maximum size of only 4.2 square kilometers (1.6 square miles). On November 30, 1965, it released and produced a flood peak of 3,100 cubic meters per second (110,000 cubic feet per second). Nonoutburst floods are compared to outburst floods by relating their unit discharge, the peak flow divided by the source area. This technique can be used to illustrate that relatively small lakes are capable of producing a very large flood. For an outburst flood from Summit Lake this unit discharge was 750 cubic meters per second per square kilometer of lake surface (70,000 cubic feet per second per square mile). By comparison, the unit discharge for nonoutburst floods in the same basin is on the order of 1 cubic meter per second per square kilometer (100 cubic feet per second per square mile). It is because of the extremely abrupt release of water that even very small glacier dammed lakes can present serious local hazards.

Areas flooded by glacier dammed lake releases are subject to serious damage. Wide flood plains are inundated to unusual depths and the high discharge rates can produce rapid erosion, deposition, and stream channel changes. The measured scour and fill of the Snow River streambed during outburst flooding during September 19–23, 1970 was 1.2 meters (4 feet) of scour and 0.7 meter (2 feet) of fill at point locations in the stream (Leveen, written commun., 1970). At Knik River, 2.4 meters (8 feet) of scour and 1.2 meters (4 feet) of fill occurred locally in the channel from July 9–11, 1965 (Leveen, written commun., 1966). Photographs (sheet 3) show 7.5 meters (25 feet) of fill at Sheep Creek near Valdez.

Serious damage may occur in spring, summer, or fall, especially when the outburst flood is superimposed on already high discharge due to melting snow or severe storms. In some places particularly hazardous situations are presented when lakes dump during the winter. Small or moderate floods at that time of year can create great damage. For instance, in January 1969 an unnamed lake (No. 27) (see photograph of Skilak Glacier, sheet 3) dammed by Skilak Glacier was released. The peak flow would have been minor if it had occurred during the summer for it caused a rise of Skilak Lake of only 0.3 meter (0.8 foot) (Harry Hulsing, oral commun., 1969). Despite this, the resulting increase in flow from the lake was sufficient to fracture the ice on Kenai River, forming great ice jams that plugged the channel at Soldotna. During a bitter cold night the backwater from these ice jams inundated roads, homes, and businesses with freezing water.

Another example is a winter flood (see Copper River graph, sheet 1), undoubtedly from the breakout of Van Cleve Lake (No. 20), which took place while the famous Million Dollar Bridge across the Copper River was under construction. O'Neel and Hawkins (1910, p. 1) reported "On February 10th, 1909, some unknown disturbance took place in Miles Glacier, and although the weather was cold, the river rose 20 feet, taking the ice out completely, and doing some damage to the temporary track across the delta below."

DIFFICULTIES IN FLOOD PREDICTION FROM GLACIER DAMMED LAKES; FLOOD HISTORIES OF FIVE RIVERS

Magnitudes and frequencies of future floods from storms or snow melt can be predicted from long-term streamflow records. For example, it may be possible to estimate the largest flood to be expected, on the average, once in 10 years or once in 100 years. Future floods from most glacier dammed lakes, however, cannot be estimated reliably using these standard statistical procedures, because the hydrologic characteristics of the drainage basin may change suddenly and discontinuously. Glacier dammed lakes which have no previous record of flooding may abruptly begin dumping, the flood sequence may change drastically, or the reservoir may cease filling due to changes in the damming glacier. For even short-term predictions of individual floods from glacier dammed lakes, up-to-date information on both the glaciers and the lakes is required in addition to the historical record.

Some of the reasons for difficulty in prediction are illustrated in the following flood histories of five rivers. Graphs showing the flood histories of four of these rivers are included on sheet 1.

Salmon River.—This river had no outburst floods from before 1890 to 1960, during which time Summit Lake, British Columbia (No. 1), impounded behind Salmon Glacier, drained over a bedrock saddle to the basin occupied by former Tide Lake (Field, 1958a; Hanson, 1932, p. 335–336; Haumann, 1960, p. 104–105; Mathews, 1965). A highway, bridge, and the town of Hyder meanwhile were built in the Salmon River valley. In 1961, Summit Lake unexpectedly and abruptly drained under Salmon Glacier and flooded the valley causing severe damage. Since 1961 the river has experienced four more glacier outburst floods from the lake. Here, an unexpected period of lake dumping followed a long history of lake stability.

Knik River.—The Knik River near Palmer is famous for destructive outburst flooding from Lake George (No. 28), which in recent years has been the largest glacier dammed lake in Alaska. Since 1918, at least, the lake emptied annually (Stone, 1963b), a pattern which continued until 1963 when no ice dam formed. Lake George again annually refilled and dumped between 1964 and 1966. The annual flooding of Knik River was so regular between 1918 and 1963 that flood experts, bridge maintenance crews, and tourists reserved a week in July or August for the event. Because of this spectacle the area has been designated as a Natural Landmark by the National Park Service. Since 1966, Knik Glacier has failed to form an ice dam and the lake has not filled. In this case, a period of regular lake dumping lapsed briefly and later ceased abruptly.

The peak discharges from 1949 to 1966 changed systematically rather than randomly as is usual for nonoutburst floods. From 1949 through 1961, there was a significant rise in the peak discharges; then during the later phase of the lake, 1962–66, the peak discharges were lower than during the preceding decade. The cause of these latter changes was undoubtedly due to a thinning of the ice at the glacier terminus. Lake George will reform in the future if Knik Glacier thickens and advances a small amount. Although this change is fairly likely, it cannot be predicted with assurance from the data presently available.

Snow and Kenai Rivers.—Outburst floods on the Kenai River above Skilak Lake originate from a glacier dammed lake (No. 26) at the headwaters of the Snow River. The first recorded outburst on this river was in December 1911 (Ellsworth and Davenport, 1915, p, 114). Outburst flooding continued, usually during November, December, or January, causing ice jams and overflow icings that damaged railroad and highway bridges (E. Estes, oral commun., 1970). The Kenai River has been gaged near Cooper Landing since 1947. Until 1961 the peaks of glacier outburst floods at this location were generally lower than the annual peaks due to snow and ice melt and rainstorms. Since 1961, all of the outburst peaks have exceeded the annual storm peaks.

The change of outburst peak discharge has been quite regular: from 1949 to 1953, the peaks decreased; from 1953 to 1967, increased; and in 1970 again decreased. These changes are judged to be related to gradual gains and losses in the glacier size and therefore are not random. Glacier ice occupies part of the basin; as this ice melts the volume of water impounded increases in proportion and the resultant outburst flood is greater.

The lake volume inferred from flood hydrographs (such as shown on sheet 1) ranged from a minimum of 94 million cubic meters (3.3 billion cubic feet) in 1953 to a maximum of 175 million cubic meters (6.2 billion cubic feet) in 1967. The time interval between lake releases also may be related to small gains or losses in glacier size. Lake releases occurred at 2-year intervals (with one 3-year exception) from 1949 to 1958, during the period with low peak discharges. Since 1958 the interval has been 3 years and the peak discharges have been higher. In this case the magnitude and frequency of outburst floods has changed markedly but systematically in a few decades.

Tazlina River.—This river basin contains four major dumping lakes—two (No. 15) formed by Tazlina Glacier and two others (No. 16) by Nelchina Glacier. Photographs (Ragle, Sater, and Field, 1965a, p. 24–27) indicate that draining of lakes No. 16 occurred sometime between April 14 and September 11, 1964, but no definite outburst floods appear on Tazlina River hydrograph for that year. Evidently the lake discharge was not rapid enough to create floods. During some other years two outbursts occur indicating the rapid release of at least two lakes on different dates. The large 1962 flood was produced by the combined release of the two largest lakes adjacent to Tazlina Glacier (Balvin, 1963), while a 1970 flood originated at Nelchina Glacier (D.K. Stewart, oral commun., 1970). The flood which destroyed the Copper River railway bridge at Chitina during a period of clear weather in August 1932 (see photograph, sheet 3) could have been caused by the release of one or more lakes in the Tazlina River basin. The flood history at Tazlina River is much more complex than for the other examples because more than one major lake is involved. The magnitude and frequency of outburst floods on the Tazlina River cannot be predicted using the historical flood record because the changes have not been systematic.

Bering River.—Berg Lake (No. 14) (see photograph, sheet 3) impounded by Bering Glacier has a complex history and presents one of the greatest potential floods of any glacier dammed lake in Alaska. When observed by Martin (1908, p. 46–48, pl. 2; also in Ellsworth and Davenport, 1915, p. 36, pl. 2) five smaller lakes occupied bays of the present large lake and the water level stood at an altitude of about 247 meters (810 feet). Strandlines as much as 60 meters (200 feet) higher indicated former levels of the lake. Martin writes "The level of the lake is oscillating. The absence of vegetation on the lower terraces shows that it has fallen in recent years. In June, 1905, it was rising several inches per day. The outlet of the lake, which is beneath the ice at the end of the long point south of First Lake, becomes choked with debris at irregular intervals. The water then rises until the pressure clears the outlet, or till the water can flow on the surface around the end of the point, when the lake is emptied, causing severe floods in the valley of Bering River."

At some unknown date since Martin's observation, but judged to have been prior to 1940 from the vegetation present in 1948, thinning of Bering Glacier lowered the ice dam and the lake level became fixed, discharging over a bedrock spillway at an altitude of about 207 meters (680 feet). Despite the lowering of the lake surface, the area of the lake has increased from 12.2 kilometers (4.7 square miles) in 1905 to 28 square kilometers (11 square miles) in 1970 because of the melting of a large ice tongue that formerly filled most of the basin. For a period of 30 or more years there have been no outburst floods from Berg Lake.

Catastrophic draining will occur in the near future if the ice dam continues to thin, for the situation is again becoming unstable. The ice dam now holding Berg Lake could be rapidly eroded, releasing the entire lake in a few hours. This could create a devastating flood sweeping the Bering River valley with a peak flow far exceeding 30,000 cubic meters per second (1,000,000 cubic feet per second).

SOME SPECIAL OUTBURST FLOOD SETTINGS

Former lakes dammed by glaciers.—In addition to the glacier dammed lakes already mentioned, a number of lakes that have not formed for several decades are of unusual interest and are shown on the maps. Several of these lakes will have no chance to reform in the foreseeable future because the damming glaciers have now completely melted away. An example is former Endicott Lake near Glacier Bay (shown on an 1892 map by Reid, 1896, pl. 86, and on International Boundary Commission map, Sheet No. 10, 1907, and later, greatly enlarged due to glacier melt, in a U.S. Navy 1929 aerial photograph).

In recent years the Alaska Highway Department has considered the feasibility of constructing a highway by way of the Taku River valley to the capitol city of Juneau. Glacier related problems were studied by Miller (1963, p. 195–200). A large lake was impounded in this valley by an advance of Taku Glacier more than 200 years ago (Lawrence, 1950, p. 208–211, fig. 6). This glacier then retreated but has readvanced 5 kilometers (3.5 miles) in the past 80 years. If this rate of advance continues, the lake could reform in about 50 years. Slowing and possible culmination of the advance before closing off the Taku River seems likely due to the great increase in glacier width as the ice spreads out in the broad Taku River valley.

Large lakes in the Alsek River valley were impounded behind Lowell and Tweedsmuir Glaciers in Canada and probably the Alsek Glacier in Alaska in recent centuries. Recent (Holocene) Lake Alsek (Kindle, 1953, p. 21–22, map 1019A), impounded by Lowell Glacier, was the largest glacier dammed lake formed in Western North America since the disappearance of the Cordilleran Ice Sheet during the late Pleistocene. At its highest level 200 or more years ago, the lake extended up the Alsek and

Dezadeash Rivers with a total length of 83 kilometers (52 miles) and covered an area of 250 square kilometers (97 square miles) including the present site of the Alaska Highway at Haines Junction. A slightly smaller lake formed in the same basin about 120 years ago. A major flood on the Alsek delta occurred in 1909 (Tarr and Martin, 1914, p. 158) which presumably was caused by the draining of a lake dammed by Lowell Glacier. Scoured valley walls, giant ripple marks on outwash deposits and sparse, youthful vegetation in the lowland areas provide spectacular evidence of the passage of gigantic floods from Lowell Glacier down the Alsek valley to the sea.

Temporary lakes caused by periodically surging glaciers.—Both Lowell and Tweedsmuir Glaciers, which dammed former lakes as mentioned above, have surface features, such as folded medial moraines, which result from periodic surges (unusually rapid flow with accompanying advance of the terminus) that occur at intervals of about 20 years. Strong surges of either of these glaciers could again repeatedly form lakes which, when released, could flood the lower Alsek Valley. Lowell Glacier is of particular interest because its surface features suggest that it is subject not only to small surges, such as observed in 1950 and 1968, but also to very large surges occurring at intervals of perhaps 80 to 150 years. Should one of these large surges occur, the ice dam in the Alsek Valley would recreate Recent (Holocene) Lake Alsek which might inundate parts of the Alaska Highway and cause devastating floods downstream when the lake water was released.

Another hazardous situation could be produced by a strong surge of Black Rapids Glacier in the Alaska Range. This glacier evidently dammed the Delta River about 1830 ± 40 years judging from description of the scene by Mendenhall (1899, p. 328) and moraines dated by Reger and Péwé (1969). A surge of similar magnitude could inundate part of the Richardson Highway and create severe floods in the Delta and Tanana River valleys. More than 200 surging glaciers have been identified in Alaska and adjacent Canadian provinces (Post, 1969). Practically all surging glaciers block lateral valleys during their rapid advances, causing glacier dammed lakes to form and resulting in floods when the lakes release (see photographs of Tikke Glacier, sheet 3). The accompanying maps show the lakes created by glacier surges in the past decade.

Other potential future lakes.—Advancing glaciers can block side valleys forming new lakes. A striking example of this may occur around 1990 if the vast Hubbard Glacier, 120 kilometers (74 miles) in length and covering an area of 3,800 square kilometers (1,470 square miles), continues to advance at its current rate. The ice will close off Russell Fiord (No. 13), a 45-kilometer (28-mile) long arm of the sea, which will then become a fresh water lake (see photograph, sheet 3). A glacier dammed lake was charted in this valley "by the Russian Booligin in 1807 and Lieut. Khromtchenko in 1823" (Tarr and Martin, p. 108). This lake, at an altitude of 50 meters (160 feet), overflowed to the south as indicated by underfit streams in the area today.

New lakes can also form adjacent to receding glaciers as the ice melts from lateral embayments; this is now occurring at two points in Desolation Valley (lake No. 9) (see photograph, sheet 3). Other sites for potential lakes, shown on the accompanying maps, are in large depressions presently occupied by nearly stagnant glacier ice.

Outburst floods caused by river icings.—In interior Alaska during winter months, river icings (aufeiss) occur in many places and in some situations build up at the outlets of lakes. Outburst flooding may occur when these ice dams fail. In March 1971, H. Livingston, K. Kahler, and A. Tatro of the Alaska Department of Highways observed a flood which covered a portion of the Richardson Highway near Rainbow Mountain with freezing slush.

Outburst floods from glaciers on volcanoes.—Although few ice dammed lakes are known to exist on Alaska's glacier sheathed volcanoes (shown on the accompany maps by red stars), these peaks present unusual flood hazards.

The Icelandic and Washington jökulhlaups all occurred in volcanic areas or on volcanic peaks. A direct relationship between vulcanism and these floods has not been determined for most cases. Alaskan ice-sheathed volcanoes doubtless present similar flood hazards and catastrophic outburst floods may occur without warning. These volcanoes, many of which are intermittently active, present even greater hazards when eruptions occur.

Very rapid melting of glacier ice can result from release of volcanic heat. During the eruption of Redoubt Volcano, beginning on January 24, 1966, a large amount of water and mud descending from the summit crater destroyed the upper reaches of an unnamed glacier and covered the lower part with debris (see photographs, sheet 3). The flood waters then proceeded down Drift River (Wilson and Forbes, 1969, p. 4511). The 1953 eruption of Mount Spurr (Juhle and Coulter, 1955; Nielsen, 1963, p. 136–138) melted the glacier ice located in the crater of Crater Peak, eroded a deep gorge in the side of the mountain and swept away part of the margin of an unnamed glacier. The resulting mudflow dammed Chakachatna River forming a lake more than 8 kilometers (5 miles) in length. These two relatively small eruptions serve to emphasize the flood hazards that could be presented by large eruptions.

SUMMARY

Floods resulting from Alaska glacier dammed lakes present a serious and increasing hazard to the growing population of the State. The number of lakes varies widely during the seasons and from year to year; the 750 lakes identified in this report indicate their abundance. Large lakes are most frequently found where valley glaciers block off ice-free side valleys; most commonly the lakes are small and located along the glacier margins below the firn line.

Although most smaller lakes fill in early summer and have drained by late August, the time of dumping of glacier dammed lakes occurs when the basins fill to critical levels and has little relationship to weather patterns. Thus flooding may occur at any time of year. Floods superimposed on high discharge due to meltwater runoff or storms create unusual hazards in summer; in winter even small floods can raise the ice on rivers causing ice jams and serious flooding.

Usual methods of storm flood frequency analysis should not be applied to floods from glacier dammed lakes. Due to changes in the glaciers, new lakes may form, old ones may be destroyed, or the frequency and/or volume of discharge may be altered. Each lake has a unique past and future, and up-to-date data on the lakes and glaciers are required for even short-term flood predictions. Flood histories of Salmon, Knik, Kenai, Tazlina, and Bering Rivers illustrate how variable the lake discharge regimes can be.

New lakes may form where glaciers advance; Hubbard Glacier may block Russell Fiord around 1990 creating a lake 45 kilometers (28 miles) in length. Lakes may also form subglacially or in depressions on or adjacent to receding glaciers. In the past 200 years several very large former lakes have disappeared due to melting or retreat of glaciers; a large former lake dammed by Taku Glacier probably will not reform in 50 years even though the glacier has been advancing strongly since 1890. Recent Lake Alsek, largest glacier dammed lake in Western North America in recent centuries which rose to high levels about 120 and 200 years ago, could reform if Lowell Glacier were to surge strongly. Many other surging glaciers form lakes when advancing; a strong surge of Black Rapids Glacier could block the Delta River creating major floods.

Large floods can also be released from glaciers with no visible lakes. Lakes dammed by river icings in interior Alaska can create outburst floods. Glacier sheathed volcanoes present serious outburst flood hazards particularly when eruptions occur; recent eruptions of Redoubt Volcano and Mount Spurr produced floods resulting from glacier melt.

CONCLUSION: A NEED FOR RECOGNIZING HAZARDOUS AREAS AND FOR MONITORING OF GLACIER DAMMED LAKES

Floods from the outburst of glacier dammed lakes have caused considerable loss of property, damage to transportation links, and some danger to human life in Alaska. As man and his works move into new areas in or below glacier-clad mountains, the hazards created by glacier dammed lakes will become increasingly serious. The dangers can be mitigated by two actions: recognition of hazardous areas and surveillance of dangerous lakes in order to provide flood warnings.

This atlas delimits specific areas of known or presumed hazard from glacier dammed lake outbursts. Detailed studies can define the dangers more precisely. Flood inundation mapping should be done for each future outburst flood in especially hazardous areas. Areas where flood data should be collected are identified in the table.

All flood hazards from glacier dammed lakes should be carefully evaluated by studying hydrological, glaciological, historical, and other pertinent data before planning highways, pipelines, and other economic improvements in downstream areas. Wherever practical, present and potential outburst flood areas should be avoided. All structures in hazardous zones should be engineered to withstand stream erosion and deposition, severe flooding, and winter ice jams.

For some situations (identified in the table) monitoring of lake levels and ice jam characteristics is suggested. This monitoring can take many forms. Periodic aerial photography, as a first step, yields information on long-term changes in the lake and its bounding glacier. Sensors such as water-stage indicators might eventually be placed on certain lakes; preferably these would be tied to real time data acquisition systems so that warning of approaching danger could be recognized immediately. Because of the systematic nature of changes in outburst flood frequency and magnitude in certain cases (for example, Lake George [No. 28], lake above Snow River [No. 26]) prediction of outbursts can be made utilizing, in addition to hydrological information, glaciological data such as mass balance or changes in glacier thickness. Existing glacier research programs at nearby locations might provide relevant data.

Most major hazards in nature, such as earthquakes and major storms, are virtually impossible to predict. Glacier dammed lakes, especially the large ones, are clearly visible so that there is little need for ignorance about the location or extent of the hazard. Furthermore, simple monitoring or study of individual lakes makes possible approximate predictions of outburst frequency, magnitude, and perhaps even timing.

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