The formation and failure of natural dams

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ABSTRACT

Of the numerous kinds of dams that form by natural processes, dams formed from landslides, glacial ice, and late-neoglacial moraines present the greatest threat to people and property. Landslide dams form in a wide range of physiographic settings. The most common types of mass movements that form landslide dams are rock and debris avalanches; rock and soil slumps and slides; and mud, debris, and earth flows. The most common initiation mechanisms for dam-forming landslides are excessive rainfall and snowmelt and earthquakes.

Landslide dams can be classified into six categories based on their relation with the valley floor. Type I dams (11% of 184 landslide dams from around the world that we were able to classify) do not reach from one valley side to the other. Type II dams (44%) span the entire valley floor, in some cases depositing material high on opposite valley sides. Type III dams (41%) move considerable distances both upstream and downstream from the landslide failure. Type IV dams (<1%) are rare and involve the contemporaneous failure of material from both sides of a valley. Type V dams (<1%) also are rare and are created when a single landslide sends multiple tongues of debris into a valley and forms two or more landslide dams in the same reach of river. Type VI dams (3%) involve one or more failure surfaces that extend under the stream or valley and emerge on the opposite valley side.

Many landslide dams fail shortly after formation. In our sample of 73 documented landslide-dam failures, 27% of the landslide dams failed less than 1 day after formation, and about 50% failed within 10 days. Overtopping is by far the most common cause of failure. The timing of failure and the magnitude of the resulting floods are controlled by dam size and geometry; material characteristics of the blockage; rate of inflow to the impoundment; size and depth of the impoundment; bedrock control of flow; and engineering controls such as artificial spillways, diversions, tunnels, and planned breaching by blasting or conventional excavation.

Glacial-ice dams can produce at least nine kinds of ice-dammed lakes. The most dangerous are lakes formed in main valleys dammed by tributary glaciers. Failure can occur by erosion of a drainage tunnel under or through the ice dam or by a channel over the ice dam. Cold polar-ice dams generally drain supraglacially or marginally by downmelting of an outlet channel. Warmer, temperate-ice dams tend to fail by sudden englacial or subglacial breaching and drainage.

Late-neoglacial moraine-dammed lakes are located in steep mountain areas affected by the advances and retreats of valley glaciers in the last several centuries. These late-neoglacial dams pose hazards because (1) they are sufficiently young that vegetation has not stabilized their slopes, (2) many dam faces are steeper than the angle of repose, (3) these dams and lakes are immediately downslope from steep crevassed glaciers and near-vertical rock slopes, and (4) downstream from these dams are steep canyons with easily erodible materials that can be incorporated in the flow and increase flood peaks. The most common reported failure mechanism is overtopping and breaching by a wave or series of waves in the lake generated by icefalls, rockfalls, or snow or rock avalanches. Melting of ice cores or frozen ground and piping and seepage are other possible failure mechanisms.

Natural dams may cause upstream flooding as the lake rises and downstream flooding as a result of failure of the dam. Although data are few, for the same potential energy at the dam site, downstream flood peaks from the failure of glacier-ice dams are smaller than those from landslide, moraine, and constructed earth-fill and rock-fill dam failures. Moraine-dam failures appear to produce some of the largest downstream flood peaks for potential energy at the dam site greater than 10^{11}–10^{12} joules. Differences in flood peaks of natural-dam failures appear to be controlled by dam characteristics and failure mechanisms.

> In the Oisans, Western Alps, a [land]slip in 1181 made a lake ten kilometers long, known as Lac de St. Laurent, and the farmers of the valley became fishermen. . . . (Davis, 1882, p. 370–371)

INTRODUCTION

There are many ways in which natural lakes and their dams can form in nature. A general but useful classification of lake basins was proposed by Davis (1882), who categorized lake basins as constructive, destructive, and obstructive. This report is concerned with only one of Davis' classifications, that of obstructive basins. Obstructive barriers include landslide dams, glacier-ice dams, moraine dams, volcanic dams, fluviatile dams, eolian dams, coastal dams, and organic dams (Table 1).

Investigation of the hazards associated with natural dams indicates that despite the great variety of natural dams, only three kinds pose a widespread threat to people and property: landslide dams, glacier-ice dams, and late-neoglacial–age moraine dams. There are many case studies of individual natural-dam failures, but an integrated view of the phenomenon as a whole does not exist. This report uses information from a large number of individual case studies to draw comprehensive conclusions about this important natural process. The data base used for this investigation consists of information on approximately 225 natural dams, the formation and(or) failure of which have been documented in the literature or are known to us from our own field investigations. This data base is believed to be sufficiently large and comprehensive that the conclusions in this report will not radically change even though it is recognized that there are some reported events not known to us and far more events that have never been recorded or reported.

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TABLE 1. TYPES OF OBSTRUCTIVE NATURAL DAMS

Type of dam	Example
Volcanic dams	
Volcanic peaks	Lake Nicaragua, Nicaragua (Hutchinson, 1957)
Lava flows	Snag Lake, California (Finch, 1937)
Pyroclastic flows	Rio Magdalena Lake, Mexico (Silva and others, 1982)
Landslide dams	
Slides/slumps	Earthquake Lake, Montana (Hadley, 1964)
Mud/debris/earth flows	Lake San Cristobal, Colorado (Crandell and Varnes, 1961)
Rock/debris avalanches	Spirit Lake, Washington (Meyer and others, 1986)
Liquefaction of sensitive clays	Yamaska River Lake, Quebec, Canada (Clark, 1947)
Peat slides	Addergoole Bog Lake, Ireland (Ousley, 1788)
Scree	Goatswater, United Kingdom (Marr, 1916)
Glacial dams	
Ice	Gapshan Lake (Shyok), Pakistan (Mason, 1929)
Moraine	Nostetuko Lake, British Columbia, Canada (Blown and Church, 1985)
Ice and snow avalanche	Rio Plomo, Argentina (King, 1934)
Fluviatile dams	
Tributary sediments	Lake Pepin, Minnesota-Wisconsin (Davis, 1882)
Main-channel sediments (lateral lakes)	Lake Tung-ting, China (Hutchinson, 1957)
Alluvial fans	Lake Tulare, California (Hutchinson, 1957)
Deltas	Blue Lakes, California (Davis, 1933)
Levee deposits (oxbow lakes)	Old River, Louisiana (Campti quadrangle, U.S. Geological Survey)
Eolian dams	
Dunes	Moses Lake, Washington (Russell, 1893)
Coastal dams	
Bay-bars	Freshwater Lagoon, Eureka, California (Cotton, 1941)
Organic dams	
Logs and other vegetation	Lake Okeechobee, Florida (Hutchinson, 1957)
Beaver dams	Beaver Lake, Montana (Hutchinson, 1957)

Note: the most dangerous of the dams are underlined. Table modified from Davis (1882) and Hutchinson (1957).

Some natural dams have economic benefits, such as hydropower generation (Anderson, 1948; Adams, 1981) and recreation (Jones and others, 1985), but they also can constitute serious hazards. A great deal of information is available about the types and characteristics of constructed dams and the causes and consequences of their failure, but similar information about natural dams is almost nonexistent, despite the fact that natural dams are far more numerous than constructed dams.

Natural dams hold most of the records for size and flood magnitude following failure. The largest flood known to have occurred on the surface of the earth, the "Spokane flood," which carved the channeled scablands in eastern Washington State between 16,000 and 12,000 yr ago, was the result of failure of a natural ice dam near what is now Missoula, Montana (Bretz and others, 1956; Baker, 1973). Another extraordinary flood was that caused by the overflow of Pleistocene Lake Bonneville at Red Rock Pass near what is now Preston, Idaho (Malde, 1968), about 14,000 yr ago (Scott and others, 1980). The flood was caused by the overtopping and failure of a natural alluvial-fan dam (Gilbert, 1878; Malde, 1968). In 1911, an earthquake in the Soviet Union triggered a rock avalanche (the Usoy landslide), with a volume of 2.0 to 2.5 billion m^3, which dammed the Murgab River. This landslide dam is about 550 m high, and the impounded lake (Lake Sarez) overflows the dam (Berg, 1950; Hutchinson, 1957; Gaziev, 1984). The Usoy landslide dam is thus nearly twice as high as the world's largest constructed dam, the Nurek earth-fill dam, also in the Soviet Union, which has a height of 315 m.

The purposes of this paper are to (1) document the methods by which the most dangerous types of natural dams form, (2) discuss what constitutes the stability or instability of the dams, (3) compare some of the physical dimensions of the dams and lakes, (4) document the mechanisms by which some of these natural dams fail, and (5) compare some of the characteristics of the resulting downstream flooding.

LANDSLIDE DAMS

Landslide dams are remarkably diverse in their formation, characteristics, and longevity. Two of the earliest recorded flooding catastrophes due to landslide dams occurred in Switzerland in A.D. 563 (Eisbacher and Clague, 1984) and in central Java in A.D. 1006 (Holmes, 1965, p. 485–487). Many landslide dams have failed catastrophically, causing major flooding and loss of life. At least 2,423 people died in the 1933 flood caused by failure of the large Deixi landslide dam on the Min River in central China (Li and others, 1986). A graphic account of the consequences of the failure of a landslide dam in the Indus River valley, India, has been provided by Mason (1929). Additional hazards occur upstream of a landslide dam within the area of natural impoundment.

Geomorphic Settings of Landslide Dams

Landslide dams form most frequently where narrow steep valleys are bordered by high rugged mountains. This setting is common in geologically active areas where earthquakes, volcanoes, or glacially oversteepened slopes occur. These areas in many cases contain abundant landslide source materials, such as sheared and fractured or hydrothermally altered bedrock, and experience triggering mechanisms to initiate landslides. Steep narrow valleys require relatively small volumes of material to form dams; thus even small mass movements present a potential for forming landslide dams. Such dams are much less common in broad open valleys, but in areas where rivers have incised lacustrine or marine deposits, slides and slumps or sensitive-clay failures have formed landslide dams (Evans, 1984; Clark, 1947).

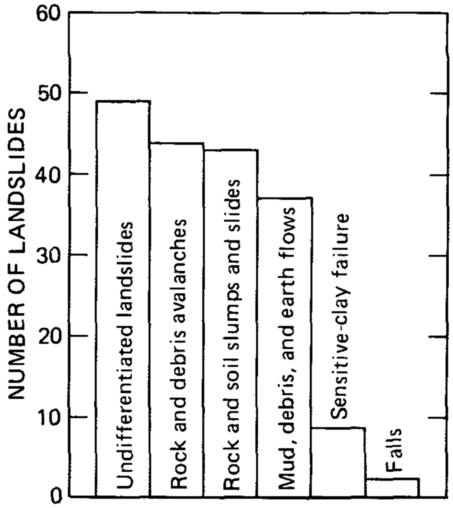


Figure 1. Distribution of landslide dams by type of landslide, based on 183 cases from the literature and the authors' experience. Mass-movement processes that actually emplaced the landslide dams are shown, even though the initial slope failures may have resulted from different landslide processes. Classification is based on Varnes (1978). (Modified from Schuster and Costa, 1986a.)

Types of Mass Movements that Form Landslide Dams

Study of 184 landslide dams has shown that a broad range of mass-movement types can cause damming (Fig. 1; Table 2). Most landslide dams, however, are caused by avalanches, slumps and slides, and flows. Relatively few dams have been caused by slope failure in sensitive clays or by rock and soil falls. The number of dams resulting from failure of sensitive clays is small because of the limited extent of sensitive clays and their common occurrence in areas of

TABLE 2. WELL-DOCUMENTED EXAMPLES OF LANDSLIDE DAMS FORMED BY SPECIFIC CLASSES OF LANDSLIDES

Landslide class and name	Year	Dammed river	State/ country	Landslide volume (m^3)	Blockage dimensions			Lake dimensions		Dam failed?	References
					Height (m)	Length (m)	Width (m)	Length (km)	Volume (m^3)		
SLIDES/SLUMPS											
Deixi landslide	1933	Min River	Sichuan, China	150×10^6	255	400	1,300	17	400×10^6	Yes	Chang, 1934; Li and others, 1986
Lower Gros Ventre landslide	1925	Gros Ventre River	Wyoming, U.S.A.	38×10^6	70	900	~2,400	6.5	80×10^6	Yes	Emerson, 1925; Alden, 1928
Tsao-Ling rock slide	1941–1942	Chin-Shui-Chi River	Taiwan	250×10^6 (two slides)	217	1,300	2,000	—*	157×10^6	Yes	Chang, 1984
Cerro Condor–Sencca rock slide	1945	Mantaro River	Peru	5.6×10^6	100	250	580	21	300×10^6	Yes	Snow, 1964
Madison Canyon rock slide	1959	Madison River	Montana, U.S.A.	21×10^6	60–70	500	1,600	10	—	No	Hadley, 1964; Knight and Bennett, 1960
Thistle earth slide	1983	Spanish Fork River	Utah, U.S.A.	22×10^6	~60	200	600	5	78×10^6	No	Kaliser and Fleming, 1986
MUD/DEBRIS/EARTH FLOWS											
Slumgullion earth flow	1200–1300	Lake Fork, Gunnison River	Colorado, U.S.A.	$50–100 \times 10^6$	40 (rough estimate)	500	1,700	3	—	No	Crandell and Varnes, 1961
Gupis debris flow	1980	Ghizar River	Pakistan	—	30	200	300	5	—	No	Nash and others, 1985
Polallie Creek debris flow	1980	East Fork, Hood River	Oregon, U.S.A.	$70–100 \times 10^3$	11	—	230	—	105×10^3	Yes	Gallino and Pierson, 1985
ROCK/DEBRIS AVALANCHES											
Usoy landslide	1911	Murgab River	Tadzhikistan, U.S.S.R.	$2.0–2.5 \times 10^9$	301 (Bolt) 550 (Gasiev)	1,000	1,000	53	—	Partial failure	Gasiev, 1984
Tanggudong debris slide/avalanche	1967	Yalong River	Sichuan, China	68×10^6	175	650	3,000	53	680×10^6	Yes	Li and others, 1986
Mayunmarca rock slide/debris avalanche	1974	Mantaro River	Peru	1.6×10^9	170	1,000	3,800	31	670×10^6	Yes	Hutchinson and Kojan, 1975; Lee and Duncan, 1975
Mount St. Helens rock slide/debris avalanche	1980	North Fork, Toutle River	State of Washington, U.S.A.	2.8×10^9	Avg. = 45	800 (Spirit Lake)	24×10^3 (Spirit Lake)	5.5 (Spirit Lake)	259×10^6 (Spirit Lake)	No (Spirit Lake)	Meyer and others, 1986
LIQUEFACTION OF SENSITIVE CLAYS											
	1898	Riviere Blanche	Quebec, Canada	2.6×10^6	8	400	3,200	—	—	Yes	Dawson, 1898
	1945	Yamaska River	Quebec, Canada	117×10^3	3-4	75	425	—	—	Yes	Clark, 1947

*Dashes indicate that the authors were unable to obtain significant data.

low relief. The number of dams resulting from falls is small because the volumes of material constituting failures of this type commonly are small.

In general, the highest landslide dams form in steep-walled, narrow valleys because there is little area for the landslide mass to spread out. Large-volume earth and rock slumps and slides, and rock and debris avalanches, are particularly likely to form high dams in narrow valleys because they occur on steep slopes and in most cases have high velocities that allow complete stream blockage before the material can be sluiced away. Commonly, large landslide dams are caused by complex landslides that start as slumps or slides and transform into rock or debris avalanches. An outstanding example was the 2.8-km^3 rockslide/debris avalanche (the world's largest historic landslide) associated with the major 1980 eruption of Mount St. Helens, Washington. This high-velocity landslide originated as a rockslide on the side of the volcano, then transformed into a debris avalanche and traveled 24 km down the North Fork Toutle River valley, impounding or enlarging five large lakes; only the three largest remain (Meyer and others, 1986).

If the basal failure zone of a landslide extends beneath the valley floor, upward movement of the stream bed itself can alter gradients and form shallow lakes. In this situation, downstream flooding is not great because the lakes are small, outlet gradients are low, and the stream-bed material may be difficult to erode.

Mud, debris, and earth flows form a significant percentage of the landslide dams reviewed. Most of these dams have been caused by relatively high-velocity debris flows issuing from tributary valleys to briefly block rivers in main valleys. Generally, dams formed in this manner are not high, and if composed of noncohesive material, they commonly overtop soon and breach rapidly (Li and others, 1986). Cohesive volcanic debris flows may form stable dams that last for thousands of years (Scott, 1985). Other kinds of flows are much slower or may form long-lived dams. An example is the 6.5-km-long Slumgullion earthflow that dammed the Lake Fork of the Gunnison River in Colorado about 700 years ago, impounding 3-km-long Lake San Cristobal (Crandell and Varnes, 1961).

Two sensitive-clay failures that formed landslide dams both occurred in shallow broad valleys in sensitive marine clays (Table 2). The

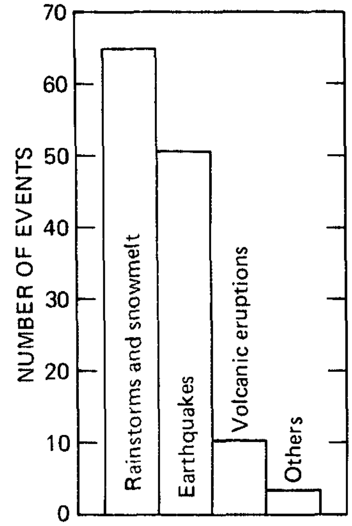


Figure 2. Causes of landslides that have formed dams, based on 128 cases from the literature and the authors' experience. Multiple dams produced by the same event were counted as one dam. (Modified from Schuster and Costa, 1986a.)

dams were low broad blockages that failed by overtopping within a few hours or days.

There are only two known reports of landslide dams formed by rock or earth falls. One was the 1943 "cliff fall" of the bank of the Grande Riviere du Chene in marine clay in Quebec (Clark, 1947); the other was a rock fall that impounded Lake Yashinkul in the central Soviet Union in 1966 (Pushkarenko, 1982).

Causes of Dam-Forming Landslides

The two most important processes in initiating dam-forming landslides are excessive precipitation (rainfall and snowmelt) and earthquakes (Fig. 2). These processes account for 90% of the landslide dams investigated. Volcanic eruptions constitute the third most significant landslide-dam–forming process (about 8%). Other mechanisms, such as devegetation and stream undercutting and entrenchment, account for the remaining 2%.

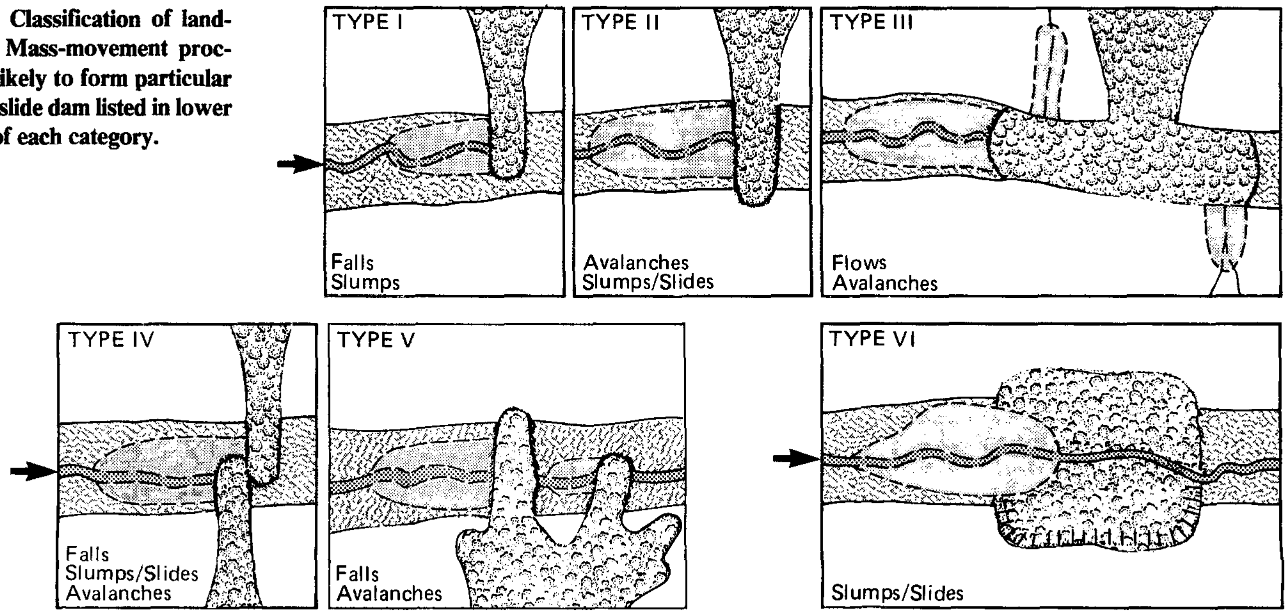
Numerous landslide dams can be formed by a single rainstorm or earthquake. In 1889 in the Totsu River basin, Japan, heavy rainfall produced 53 landslide dams in the upper 1,100 km^2 of the watershed (Swanson and others, 1986). The 1929 Buller earthquake (magnitude 7.6) in the northwestern part of South Island, New Zealand, produced landslides that formed at least 11 landslide-dammed lakes (Adams, 1981). In 1783, an earthquake in Calabria, Italy, triggered mass movements that formed 215 landslide-dammed lakes (Cotecchia, 1978).

An unusual series of events illustrating the formation and destruction of a landslide dam has been documented for the Tsao-Ling landslide in central Taiwan (Chang, 1984). This case demonstrates just how complex natural-dam processes can be. In 1862, a major earthquake triggered a landslide that dammed the Chin-Shui-Chi River. In 1898, the natural dam failed for unknown reasons. In December 1941, a major earthquake formed another landslide dam, 140 m high, at the same location. In August 1942, heavy rainfall caused reactivation of the landslide and the natural dam increased in height from 140 to 217 m. In May 1951, several days of intense rainfall led to the overtopping and failure of the natural dam. In the subsequent flood, 154 people were killed and 564 homes damaged. On August 15, 1979, heavy rainfall again activated the landslide, which dammed the river with a natural barrier 90 m high. Heavy precipitation continued, and 9 days later, the landslide dam was overtopped and failed, causing severe flooding.

Classification of Landslide Dams

Landslide dams can be classified geomorphically with respect to their relations with the valley floor (Swanson and others, 1986) (Fig. 3). Type I dams are small in contrast to the width of the valley floor and do not reach from one valley side to the other. Type II dams are larger and span the entire valley floor, in some cases depositing material high on opposite valley sides. Type III dams fill the valley from side to side, move considerable distances upvalley and downvalley from the failure, and typically involve the largest volume of landslide material. Type IV landslide dams form by the contemporaneous failure of material from both sides of a valley. The landslides can adjoin head-to-head in the middle of the valley, or they can juxtapose one another. Type V landslide dams form when the same landslide has multiple lobes of debris that extend across a valley floor and form two or more landslide dams in the same reach of river. Type VI landslide dams involve one or more failure surfaces that extend under the stream or river valley and emerge on the opposite valley

Figure 3. Classification of landslide dams. Mass-movement processes most likely to form particular kind of landslide dam listed in lower left corner of each category.



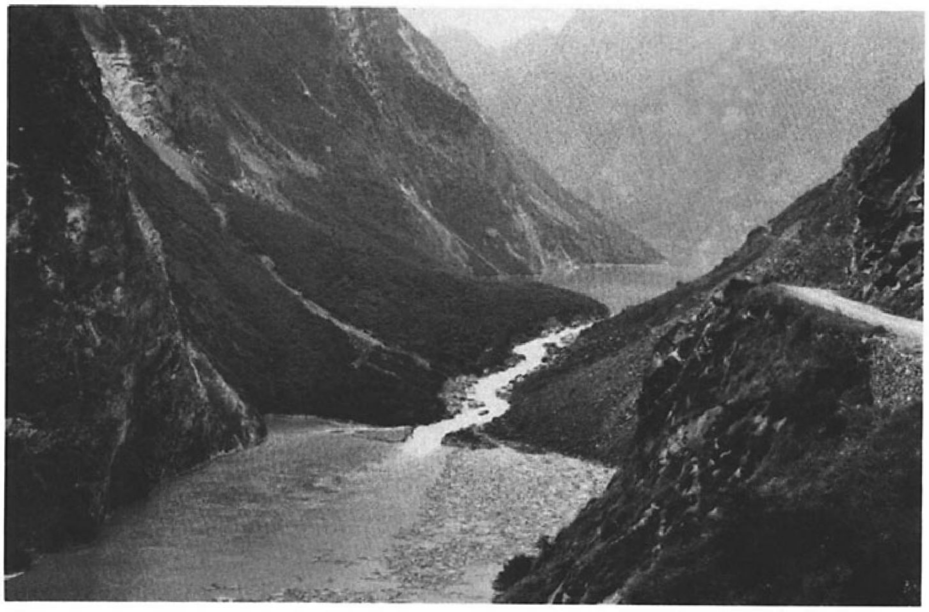


Figure 4. Photograph of view upstream along the Min River, Sichuan Province, People's Republic of China, at the remains of the 1933 earthquake-induced Yinping landslide dam, which impounded Da Lake (middle background). Xiao Lake (foreground) was impounded by another landslide dam caused by the same earthquake.

side from the landslide. These dams typically involve slow basal sliding and slumping and form lakes by raising the elevation of the streambed, changing the local gradient of the stream.

Of 184 landslide dams classified from around the world, the most common are types II (44%) and III (41%). The other types are much more infrequent (type I = 11%, type IV and type V = <1%, and type VI = 3%). Type I landslide-dam lakes commonly are small, shallow, and in most cases not hazardous. Type II landslide-dam lakes are larger and much more dangerous. Type III dams, in addition to forming large hazardous lakes behind the obstruction, can also block tributaries to the main valley, creating additional potentially dangerous lakes. This is the case at Mount St. Helens, Washington, as a result of the 1980 debris avalanche that dammed tributaries to the North Fork Toutle River. Type IV and V landslide-dam lakes can be hazardous if the valleys are narrow and the landslide volumes large enough to form high dams. Only one example of a type IV landslide dam is known, the Yinping landslide blockage of the Min River, Sichuan Province, China, which forms Da Lake (Li and others, 1986) (Fig. 4). Only one example of a type V landslide dam is known, the Slide Lake rockfall-avalanche in Glacier National Park, Montana (Butler and others, 1986). A few examples of type VI landslide dams are known from Japan (Swanson and others, 1986) and one from Colorado (East Muddy Creek landslide). This type of landslide dam typically poses less threat of downstream flooding than do the other types because it may never cause a complete blockage. The stream may continue to flow over the dam debris, so that the likelihood of abrupt overtopping and rapid incision of the dam is unlikely. Water storage usually is small and the stream gradient is not relatively steep.

Modes of Failure of Landslide Dams

A landslide dam in its natural state differs from a constructed embankment dam in that it is made up of a heterogeneous mass of unconsolidated or poorly consolidated earth material and has no engineered water barrier (impervious zone), filter zones to prevent piping, nor drain zones to control pore pressures. It also has no channelized spillway or other protected outlet; consequently, landslide dams commonly fail by overtopping, followed by breaching from erosion by the overflowing water (Fig. 5). In most documented cases, the breach has resulted from the fluvial erosion of the landslide material when headcutting originates at the toe of the dam and progressively moves upstream to the lake. When the headcut reaches the lake, breaching occurs (for example, Lee and Duncan, 1975). The breach commonly does not erode down to the original river level because many landslide dams contain some coarse material that locally armors the streambed. Smaller lakes thus can remain after dam failure.

Because landslide dams have not undergone systematic compaction, they may be porous, and seepage through the dams potentially could lead to failure by internal erosion (piping). Seeps have been noted on the downstream faces of many landslide dams. Examples are the 1925 Lower Gros Ventre landslide in northwestern Wyoming, which failed in 1927 after overtopping (Alden, 1928), and the 1945 Cerro Condor-Sencca landslide dam in Peru, which failed in 1945, probably because of "violent" seepage and piping (Snow, 1964). Although failure of landslide dams from piping and seepage is uncommon, at least three cases wherein a landslide dam actually has failed in this manner are known, however: the 1945 Cerro Condor-Sencca landslide dam, the 1966 breach of the landslide dam that impounded Lake Yashinkul on the Isfayramsay River in the south-central U.S.S.R. (Glazyrin and Reyzvikh, 1968), and the 1906 failure of the landslide dam on Cache Creek in northern California (Scott, 1970). In these failures, piping and undermining caused collapse of the dam, followed by overtopping and breaching.

A landslide dam with steep upstream and downstream faces and with high pore-water pressures is susceptible to slope failure. If the dam has a narrow cross section or if the slope failure is progressive, the crest may fail, leading to overtopping and breaching. Nearly all faces of landslide dams are at the angle of repose of the

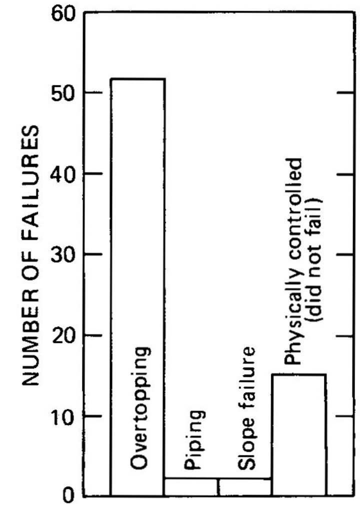


Figure 5. Modes of failure of landslide dams, based on 55 failures from the literature and the authors' experience.

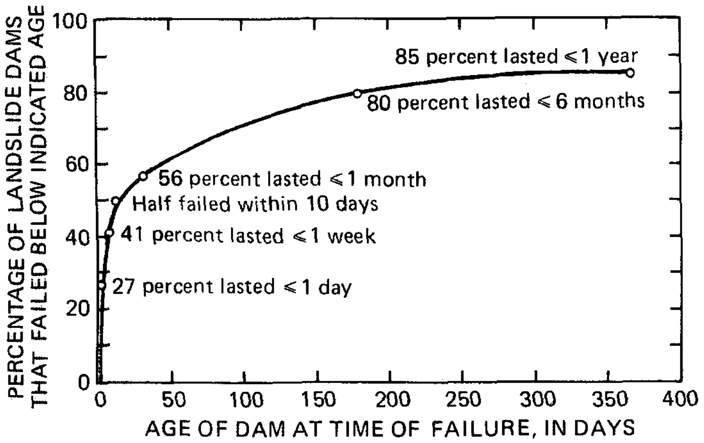


Figure 6. Length of time before failure of landslide dams, based on 73 cases from the literature and the authors' experience.

material or less, however, because they are formed dynamically. In such cases, slope failures are rare.

A special type of slope failure involves lateral erosion of the dam by a stream or river (for example, Jackson Lake, Mount St. Helens, Washington, U.S. Geological Survey, unpub. data; and Hole-in-the-Wall Gulch, Oregon, Geist and Schuster, 1986). At least one well-documented example exists in which failure of the downstream slope of a landslide dam may have contributed to over-all failure: the 1945 Cerro Condor-Sencca blockage of the Mantaro River, Peru (Snow, 1964).

Longevity of Landslide Dams

Landslide-dammed lakes may last for several minutes or several thousand years, depending on many factors, including volume, size, shape, and sorting of blockage material; rates of seepage through the blockage; and rates of sediment and water flow into the newly formed lake. Seventy-three examples of landslide-dam failures in which the time prior to failure is known are compiled in Figure 6 and indicate how dangerous landslide dams can be. Twenty-seven percent of the dams failed within 1 day of formation; 41% failed within 1 week; about 50% failed within 10 days; 80% failed within 6 months; and 85% failed within 1 yr of formation. Rapid assessment of the dam and the flooding potential is thus essential. It is important to note, however, that these percentages pertain only to landslide dams that have failed. Numerous other landslide dams have formed and not failed.

The three factors that seem to be most relevant to the longevity of a landslide dam are (1) rate of inflow to the impoundment, (2) size and shape of the dam, and (3) geotechnical characteristics of the dam. In many cases, the amount of flow in a stream, and thus, the rate at which a natural lake will fill, is directly proportional to the size of the upstream drainage area. If a landslide dam fills to some equilibrium level and does not fail, the dam still could be potentially dangerous. The Gros Ventre, Wyoming (Alden, 1928), and Lake Elizabeth, Australia (Rosengren, 1984), landslide dams did not fail until more than a year after formation. Both lakes had reached supposed stable elevations, but subsequently failed during periods of unusually high inflow.

The life of a landslide dam is apt to be short whenever a small landslide blocks a stream with a large drainage area (Swanson and others, 1986). Unless seepage through the dam equals the inflow, the dam can fill to overtopping. Rapid inflow behind a low, small landslide dam means that the new natural lake probably will fill quickly to overflowing, which may lead to breaching and failure.

Landslide dams of predominantly soft, low-density, fine-grained or easily liquefied sediment lack resistance to erosion and are hazardous. Rate of dam failure by surface erosion following overtopping is dependent on cohesive strength and friction angle of the landslide material (Fread, 1985). If the dam materials are mostly saturated, shear strength may be low, and the dam may not be able to withstand the increasing hydrostatic pressure resulting from the impoundment or the dam may erode rapidly when overtopped.

Some landslide dams are more resistant to all types of failure mechanisms than are others. The most important characteristic in preventing failure is resistance to erosion, either at the surface of the dam from surface-water runoff or within the dam from piping and seepage. As might be expected, landslide dams consisting of large or cohesive particles resist failure better than do dams containing large percentages of soils or soft rock. Landslide dams typically are much wider than constructed embankment dams. The large mass of many such blockages provides some degree of protection against failure, especially rapid failure, by any mechanism.

Sorting of landslide sediment also is an important factor. Natural poorly sorted materials with D 15/D 85 ratio greater than 5 are susceptible to internal erosion by piping (Sherard, 1979). If the material forming the landslide dam is permeable, easily eroded sediment, rising water levels behind the dam may force water through the permeable beds and lead to piping and erosion that could cause the dam to fail.

In some cases, lakes have not overtopped their dams because lake inflow is smaller than losses due to seepage, evaporation, or withdrawals for irrigation. An example is Bitang Lake in Gansu Province, China, which has stabilized at a level considerably below the crest of the landslide dam that impounded it in 1961 (Li and others, 1986).

In a few cases, outflow from landslide-dammed lakes has formed natural spillways across adjacent bedrock abutments or by channel armoring, thus preventing overtopping and possible breaching of the dams. A well-known example of a natural bedrock spillway for a landslide-dammed lake is the outlet across the left abutment of the Slumgullion earthflow in southwestern Colorado (Schuster, 1985). This natural spillway has existed for 700 yr.

Physical Measures to Improve the Stability of Landslide Dams

Construction of control measures (most commonly spillways) has been attempted in recent years on many major landslide dams as soon as possible after formation. In some cases, however, overtopping has occurred before satisfactory control measures could be constructed. This is particularly common in outlying mountainous areas where transportation of heavy construction equipment to the site is difficult.

The simplest and most common method for stabilizing landslide dams has been construction of channelized spillways either across adjacent bedrock abutments or directly over the landslide dams. A well-known example of a successful spillway across a landslide dam is the spillway constructed in 1959 by the U.S. Army Corps of Engineers on the Madison Canyon landslide, Montana (Harrison, 1974) (Fig. 7).

Spillways excavated across landslide dams are not always successful in preventing dam failure

Figure 7. Photograph of the landslide dam formed by the 1959 Madison Canyon landslide, Montana, and of Earthquake Lake, which it impounds. (Photograph by J. R. Stacy, U.S. Geological Survey.)

and subsequent flooding because they sometimes are eroded rapidly by outflow waters. Such was the case for the 1976 landslide dam of the Rio Quemaya in Guatemala where highway workers trenched the landslide dam to drain the lake. Drainage was too rapid, causing a flood that swept away several people (Harp and others, 1981).

In a few cases, large-scale blasting has been used to excavate new river channels through landslide dams. This technique was used in 1981 to open a channel through the Zhouqu landslide dam on the Bailong River in Gansu Province, China (Li and others, 1986). Other methods of stabilizing lake levels behind landslide dams and preventing overtopping include pipe and tunnel outlets and diversions. Both a pipe and a tunnel have been used to control discharge from Spirit Lake, Mount St. Helens, Washington (Sager and Chambers, 1986), and at Thistle, Utah (Kaliser and Fleming, 1986).

GLACIER DAMS

Glacier dams are dams that impound water in, on, beneath, or behind masses of glacial ice. These dams can occur in any area covered by continental or valley glaciers. Other, related natural dams not discussed include icefalls (Ballantyne and McCann, 1980), snow and ice avalanches (King, 1934), and snowbanks (Church, 1972).

Jökulhlaup ("glacier burst") is the Icelandic term for a flood caused by the sudden and usually catastrophic release of water impounded within or behind glacier ice (Thorarinsson, 1953). Some of the largest floods known to have occurred in the history of the Earth were the result of the failure of ice dams during the waning stages of the Pleistocene. The failure of ice dams has caused large loss of life and property damage in many places, including Iceland (Thorarinsson, 1939, 1953, 1957); northern India (Hewitt, 1982); Pakistan (Nash and others, 1985); Peru (Lliboutry and others, 1977); Norway (Aitkenhead, 1960); Alaska (Post and Mayo, 1971); Washington and Oregon (Richardson, 1968); Switzerland, Austria, France, and Italy (Eisbacher and Clague, 1984); and Canada (Clarke, 1982; Young, 1980) (Table 3).

Geomorphic Settings of Glacier Dams

Glacier dams can form in any area covered by or adjacent to continental or alpine glaciers (Fig. 8). Glacial ice may obstruct drainage and form lakes in numerous ways (Table 4; Fig. 9).

One of the most hazardous kinds of ice-dammed lakes is category G in Table 4, lakes formed in main valleys dammed by tributary-valley glaciers. These lakes can be large, and the ice dam can be relatively small. These dams in most cases form as a result of glacial surges, in which the velocity of a tributary glacier temporarily can increase 10 to 100 fold (Meier and Post, 1969; Budd, 1975). In the upper Indus River valley of Pakistan, at least 18 tributary glaciers have dammed major valleys (Hewitt, 1982). The Chong Khumdan glacier on the

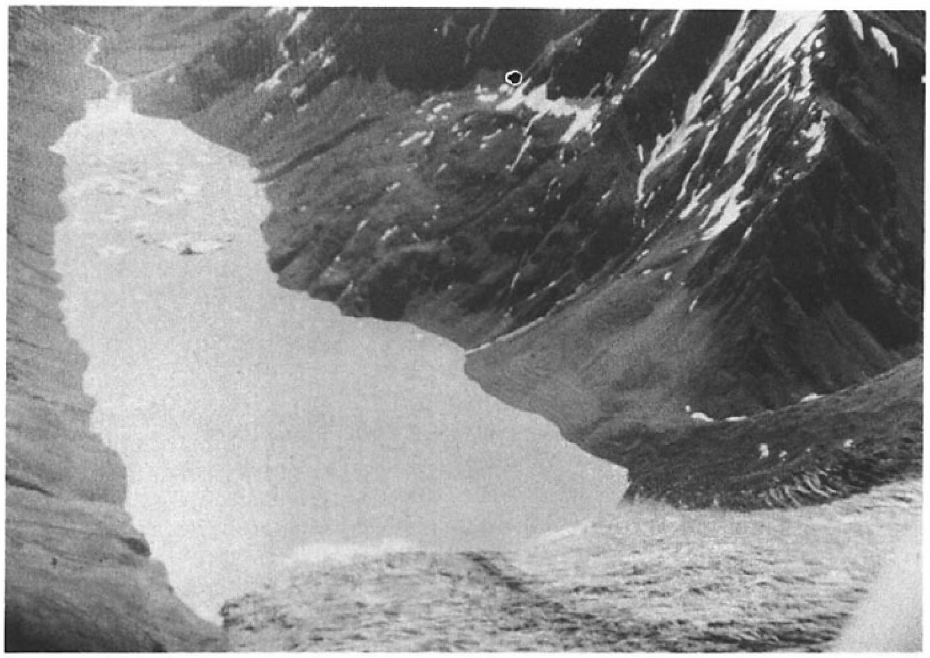


Figure 8. Photograph of a glacier-dammed lake in a tributary valley (type D, Table 4), Coast Mountains, Alaska. Note the strand lines indicating previously higher lake levels. (Photograph by W. C. Bradley, University of Colorado.)

TABLE 3. WELL-DOCUMENTED EXAMPLES OF GLACIER DAMS THAT HAVE FAILED, PRODUCING JÖKULHLAUPS

Lake name	Location	Year failed	Dam height (m)	Lake volume (m^3)	Flood peak (m^3/s)	References
Missoula*	Montana, U.S.A.	16,000–12,000 yr B.P.	1,078	$2,184,000 \times 10^6$	21.3×10^6	Baker, 1973; Clarke and others, 1984
Vatnsdalur	Iceland	1898	372	120×10^6	3,000	Thorarinsson, 1939
Chong Kumdan (Shyok)	India	1929	120	$1,350 \times 10^6$	22,650	Gunn, 1930; Hewitt, 1982
Demmevatn	Norway	1937	406	11.6×10^6	1,000	Clague and Mathews, 1973
Graenalon	Iceland	1939	535	$1,500 \times 10^6$	5,000	Thorarinsson, 1939
Gorner	Switzerland	1944	?	$>6 \times 10^6$	200	Haeberli, 1983
Gjanupsvatn	Iceland	1951	167	20×10^6	370	Arnborg, 1955
Lake George	Alaska, U.S.A.	1958	40	$1,730 \times 10^6$	10,100	Stone, 1963
Tulsequah	British Columbia, Canada	1958	210	229×10^6	1,556	Marcus, 1960
Summit	British Columbia, Canada	1965	620	251×10^6	3,260	Mathews, 1965
Ekalugad Valley	Baffin Island, Canada	1967	120	4.8×10^6	200	Church, 1972
Strupvatnet	Norway	1969	186	2.6×10^6	150	Whalley, 1971
Hazard Lake	Yukon, Canada	1978	300	19.6×10^6	640	Clarke, 1982

*Not used as data for Figure 12 or Table 6.

Shyok River, a large tributary of the Indus, is a classic example of a glacier projecting into and blocking a major valley. Numerous disastrous floods have occurred from the temporary blocking and failure of the ice dam in the valley of the Shyok River, the most notable being the flood of 1929 (Mason, 1929; Gunn, 1930).

Modes of Failure of Glacier Dams

Ice-dam failures are complicated phenomena, involving many sets of independent factors. Glacier dams often fail periodically, with return periods of 1 to >10 yr. About 95% of more than 50 jökulhlaups in the Alps occurred from June through September, with maxima in June and August (Tufuell, 1984). The failure of glacier dams can occur by erosion of a drainage channel under, through, or over the ice dam. Many ice dams fail by rapid drainage through englacial or subglacial tunnels (Gilbert, 1971). Such tunnels can be tens of kilometres long (Nye, 1976), and the outlet location can change by hundreds of kilometres from one failure to another (Sturm and Benson, 1985). The ice comprising these

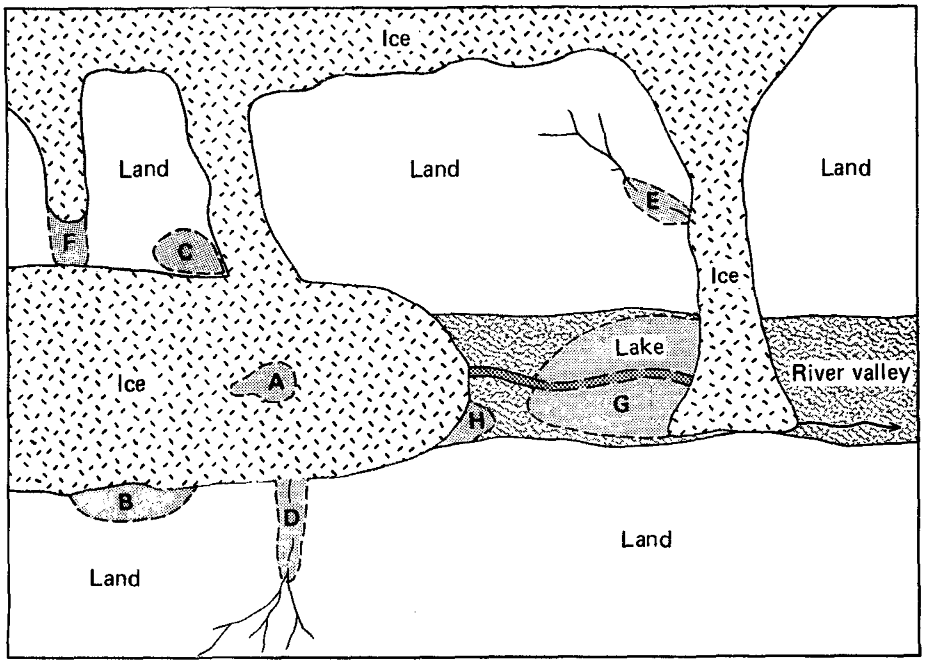


Figure 9. Classification of glacial-ice dams, keyed to Table 4.

TABLE 4. CLASSIFICATION OF ICE-DAMMED LAKES

Type of lake	Example
A. Supraglacial	Generally small and not hazardous
B. Marginal ponded	Unnamed lake, Greenland (Sugden and others, 1985)
C. Converging ice-stream ponded	Between Lake, Axel Heiberg Island, Canada (Maag, 1969)
D. Tributary stream-valley ponded	Flood Lake, British Columbia, Canada (Clarke and Waldron, 1984)
E. Tributary glacier-valley ponded	Lago Rico, Argentina (Nichols and Miller, 1952)
F. Interglacial ponded	Tulsequah Lake, British Columbia, Canada (Marcus, 1960)
G. Dammed by tributary glacier	Shyok River Lake, Upper Indus Valley, Pakistan (Gunn, 1930; Mason, 1929)
H. Proglacial ice dammed	Generally small for valley glacier, can be gigantic for continental ice sheets (for example, Glacial Lake Agassiz)
I. Miscellaneous (ice-dammed craters above volcanoes; large englacial or subglacial water bodies)	Grimsvotn, Iceland (Thorarinsson, 1953)

Note: table modified from Blachut and Ballantyne (1976).

TABLE 5. WELL-DOCUMENTED EXAMPLES OF MORAINE DAMS THAT HAVE FAILED

Lake or site name	Location	Date failed	Change in lake level (m)	Volume discharged ($m^3 \times 10^4$)	Flood peak (m^3/s)	Failure mechanism	References
Madatschferner	Austria	Aug. 5, 1874	. .	. .	. .	. .	Eisbacher and Clague, 1984
Galrittferner	Austria	Aug. 7, 1890	. .	. .	. .	Ice fall	Eisbacher and Clague, 1984
Cohup	Peru	Dec. 13, 1941	. .	. .	. .	. .	Eisbacher, 1982; Lliboutry and others, 1977
White Branch	Oregon, U.S.A.	July 1942	. .	. .	360	. .	Laenen and others, 1987
Tempanos	Argentina	1942–1953	. .	. .	. .	Excess melt water	Rabassa and others, 1979
Jancarurish	Peru	1950	21	600–1,000	7,000–8,000	Collapse of undercut glacier	Lliboutry and others, 1977
Artesoncoda	Peru	July 16–17, 1951	113	. .	. .	Ice fall	Lliboutry and others, 1977
Broken Top	Oregon, U.S.A.	Oct. 7, 1966	4.6	18.9	71	Ice fall	Nolf, 1966; this report
Squaw Creek	Oregon, U.S.A.	Sept. 7, 1970	25.6	33.3	297	. .	Laenen and others, 1987
Safuna Alta	Peru	1970	38	490 (stored in lake)	. .	Earthquake-induced piping	Lliboutry and others, 1977
Klattasine	British Columbia, Canada	June 1971–Sept. 1973	13	170	>1,000	. .	Clague and others, 1985
Moraine no. 13	Soviet Union	Aug. 3, 1977	5.2	8.64	210	Melting of frozen soil	Yesenov and Degovets, 1979
Mingbo Valley, Dudh Kosi River	Nepal	Sept. 3, 1977	30	490	1,100	Melting of ice core? Excess runoff?	Buchroithner and others, 1982; Fushimi and others, 1985
Nostetuko	British Columbia, Canada	July 19, 1983	38.4	650	11,000	Ice fall	Blown and Church, 1985
Dig Tsho	Nepal	Aug. 4, 1985	22.5	800	1,600	Ice fall	Galay, 1985; Vuichard and Zimmermann, 1987

dams behaves plastically, deforming and flowing to re-establish a blockage of drainage by closing englacial or subglacial tunnels or by squeezing breaches shut. The lake then can reform by collecting runoff from the drainage area upstream, from surface runoff from the glacier, and from sub-glacial flow into the reservoir.

Another commonly evoked failure mechanism is the hydrostatic flotation hypothesis of Thorarinsson (1953), whereby subglacial drainage becomes possible when hydrostatic pressure of water in an ice-dammed lake exceeds the ice overburden pressure in an ice dam. This excess occurs when the depth of water behind an ice dam reaches 0.9 times the height of the ice dam. The story is not so simple as measuring the lake level behind an ice dam, because some ice-dammed lakes fail before filling to 0.9 times the ice-dam height, and most lakes continue to drain well after water levels decline below this critical level. Lifting of the ice dam may be only a triggering mechanism of failure, followed by other processes that allow continued drainage of the lake, such as erosion of drainageways under the ice by escaping lake water, uneven settling of the ice dam after flotation, or formation of tension crevasses from flotation (Marcus, 1960).

Other mechanisms for failure of glacier dams include (1) slow plastic yielding of ice from hydrostatic-pressure differences between the lake and adjacent, less-dense ice; (2) crack progression under combined shear stress from glacier flow and hydrostatic pressure; (3) water overflowing the ice dam and eroding a breach into the dam; (4) subglacial melting by volcanic heat; and (5) weakening of the ice dam by earthquakes (Post and Mayo, 1971).

The type of ice forming an ice dam (cold polar and subpolar ice versus warmer temperate ice) affects the potential failure mechanisms. Glacier dams formed of cold polar and subpolar ice are relatively tight and dense, have temperatures below the pressure melting point, are usually dry at their bases, and generally drain supraglacially or marginally by downmelting of an outlet channel (Marcus, 1960; Maag, 1969). Warmer, temperature glacier dams are more fractured and less dense, have subglacial meltwater flow, and tend to fail by sudden englacial or subglacial breaching and drainage (Blachut and Ballantyne, 1976).

Longevity and Controls of Glacier Dams

Some glacier dams fail by means of noncatastrophic seasonal drainage outlets; the ice dams at Base Camp Lake, Greenland (Clement, 1984), are an example. Others fail catastrophically on an annual or near-annual basis. An example is the glacier dam that impounded Lake George, Alaska. This dam failed annually from at least 1918 until 1966 (Bradley and others, 1972). Some glacier dams fail several times during 1 yr; others fail irregularly. Irregular damming and failure are believed to be related to local climate control of glacier activity, filling rates, and lake temperatures. In some situations, the overflow outlet for a glacier-dammed lake is controlled by overflow across low bedrock cols around the perimeter of the lake (Sugden and others, 1985).

Numerous case studies of glacier-dammed lakes indicate that the frequency of glacier-dam failure is likely to change with time. Thorarinsson (1939) demonstrated that as a glacier recedes and melts, failures increase in frequency but decrease in magnitude, eventually ending with establishment of a permanent outlet. This pattern of response to glacial recession, increasing ice-dam failure, and decreasing flood magnitudes has been documented for Tulsequah Lake, British Columbia (Marcus, 1960).

Some factors appear to predicate the failure of a glacier dam. Filling to some characteristic level is one example. A unique lake level may signal the beginning of hydrostatic flotation or overtopping of the ice barrier. A glacier dam with a cyclical history of failure may continue to fail, provided no change occurs in the size or shape of the ice dam. At Strandline Lake, Alaska, precursor indications of a glacier-dam failure include (1) rapid iceberg calving from the glacier, producing numerous icebergs; (2) filling of a number of small supraglacial pools; and (3) lake-level rise to a pre-identified failure level (Sturm and Benson, 1985).

Artificial controls of the levels of glacier-dammed lakes have been attempted in several locations. In the Alps, trenching across a glacier dam or tunneling through rock or ice has allowed control of dangerous lakes (Eisbacher and Clague, 1984). This is not always successful (Mathews, 1965). In Argentina, 500-kg bombs were dropped on a glacier dam in an unsuccessful attempt to destroy the dam (Nichols and Miller, 1952).

MORAINE DAMS

Many moraine dams occur throughout the world, but the most dangerous are restricted to alpine regions affected by the advances and retreats of valley glaciers in the last several centuries in steep mountain areas. Some excellent case studies have been made of moraine-dam failures in Peru (Lliboutry and others, 1977) and in British Columbia (Blown and Church, 1985), but relatively little is known about these natural dams compared to landslide or glacier dams. Moraine-dam failures have been reported from Nepal (Galay, 1985; Vuichard and Zimmermann, 1987), India and Pakistan (Burgisser and others, 1982), the U.S.S.R. (Yesenov and Degovets, 1979), Oregon (Nolf, 1966; Laenen and others, 1987), Peru (Lliboutry and others, 1977), Canada (Clague and others, 1985), Austria (Eisbacher and Clague, 1984), and Argentina (Rabassa and others, 1979).

Geomorphic Settings of Moraine Dams

A globally synchronous readvance of glaciers during the last few centuries has been documented (Grove, 1979) and referred to as the "Little Ice Age" (Matthes, 1939) or "late-neoglacial time" (Porter and Denton, 1967). Neoglacial time ended in the late 19th century, and since then, many mountain glaciers have retreated significantly (Porter and Denton, 1967), leaving behind many moraine-dammed lakes.

There are two primary kinds of late-neoglacial moraine dams. The first kind has no surface overflow channels, and the impounded lake lies well below the rim of the dam; drainage is by seepage through the dam. The second kind of moraine dam has an overflow channel across the glacial sediments. Late-neoglacial and contemporary moraine-dammed lakes are hazards because (1) they are young and located at such high elevations that vegetation has not completely stabilized their slopes; (2) slopes are steep (some are greater than 40°); (3) thermal degradation melting an ice or snow core could render them unstable; and (4) these dams may be close to an ice front and steep, rock-walled cirques and valleys. Anomalous melt-water inflow or ice and rock falls into the lakes may precipitate waves that lead to breaching and failure of these dams.

A variety of types of moraines may form in alpine areas. Push moraines originate when glacial ice advances and bulldozes sediment into a ridge, typically less than 9 m high (Sugden and John, 1976). A typical push moraine has a shallow upstream-dipping surface overridden by the glacier and a steeper downstream face formed by material cascading down the glacier surface. Push moraines do not commonly form dams, or they contain only small lakes.

Ice-thrust moraines originate from the collection of sediment and debris eroded from the base of a glacier and thrust along shear planes to the front margin of the ice. Moraines can form to heights of 100 m or more if the glacier is on a steep gradient, flows rapidly, and actively erodes material from its boundary. Because ice-thrust moraine sediment has been at least partly overridden by the glacier, and buttressed by the retreating ice sheet, some of the dam material is partially compacted. Proximal and distal slopes of the moraine can be over steepened, and many slope angles are 40° or steeper. Ice-thrust moraine sediments are relatively compact and contain more fines than do other types of moraine dams.

Dump moraines originate from the dumping down the ice front of sediment and debris from within the ice and on the ice surface. The form and size of dump moraines are controlled by rate of ice movement, rate of surface ablation, volume of sediment in and on the ice, and melt-water effects. A dump-moraine dam will be a heterogeneous mixture because material moving from the ice to the moraine comes from diverse sources, lithologies, textures, and transport mechanisms. Dump moraines typically have steep ice-contact upstream slopes, where the moraine was buttressed by the glacier, and flatter distal downstream-facing slopes (Andrews, 1975). For large dump moraines to form, forward motion of the glacier must balance the melting rate. Till in dump moraines tends to be relatively loose, uncompacted, and free of fines. Steep slopes and uncompacted and noncohesive sediment make dump-moraine dams unstable.

Ice-cored moraines can originate when sediment and water at the base of a glacier is moved upward toward the ice surface by compression and thrusting. Ice-cored moraines can be as much as 90% ice by volume, with only thin till covers. The ice core can originate as glacial ice or snow (Ostrem, 1964). Ice cores in high-altitude or subpolar continental climates can last for 1,000 yr (Andrews, 1975). Naturally, the melting of an ice-cored moraine impounding a lake can lead to the collapse and failure of the moraine dam. The presence of an ice core in a moraine may be indicated by moist areas or seeps in moraine-dam walls above lake levels late in the summer or early autumn before subfreezing temperatures occur.

Modes of Failure of Moraine Dams

Comprehensive descriptions of the failure of moraine dams are rare (Table 5). The Cordillera Blanca and Cordillera Huayhuash of north-central Peru are regions that have an especially large number of moraines enclosing narrow, steep valleys. Nearly all glaciers of the Cordillera Blanca lie behind large moraines of late-neoglacial age and contain lakes (Lliboutry and others, 1977). In 1941, Laguna Cohup, a proglacial moraine-dammed lake, drained rapidly when the moraine dam failed. The resulting flood of mud and water (known in Spanish as "alluvion") destroyed almost half of the town of Huaraz and killed about 6,000 people (Ericksen and others, 1970; Eisbacher, 1982). This disaster led to a major effort toward control and lowering of lake levels in dangerous moraine-dammed lakes in Peru (Lliboutry and others, 1977).

One of the most comprehensive descriptions of the failure of a moraine dam is the work of Blown and Church (1985) on the failure of the moraine dam of Nostetuko Lake, British Columbia, Canada (Fig. 10). Another moraine-dam failure occurred at Klattasine Lake, British Columbia, sometime between June 1971 and September 1973 (Clague and others, 1985).

Most of the textural data from moraine dams indicate that the moraine material is silty, sandy, bouldery till, with minimal clay (less than 3% or 4%). Lake levels are controlled by seepage through the barrier and open overflow channels across the top of the moraine. Of the 15 documented cases of failures of moraine dams known to us, the mechanism of failure is known or can be reasonably estimated for nine. The most common failure mechanism is overtopping by a wave or series of waves generated by icefalls or rockfalls, or snow or rock avalanches, into the lake basin. The wave overtops the moraine dam, and augmented flow in the outlet channel causes erosion of the channel that permits increased flow from the lake as it begins to drain.

Avalanches into standing bodies of water are capable of producing destructive and erosive waves that frequently achieve heights greater

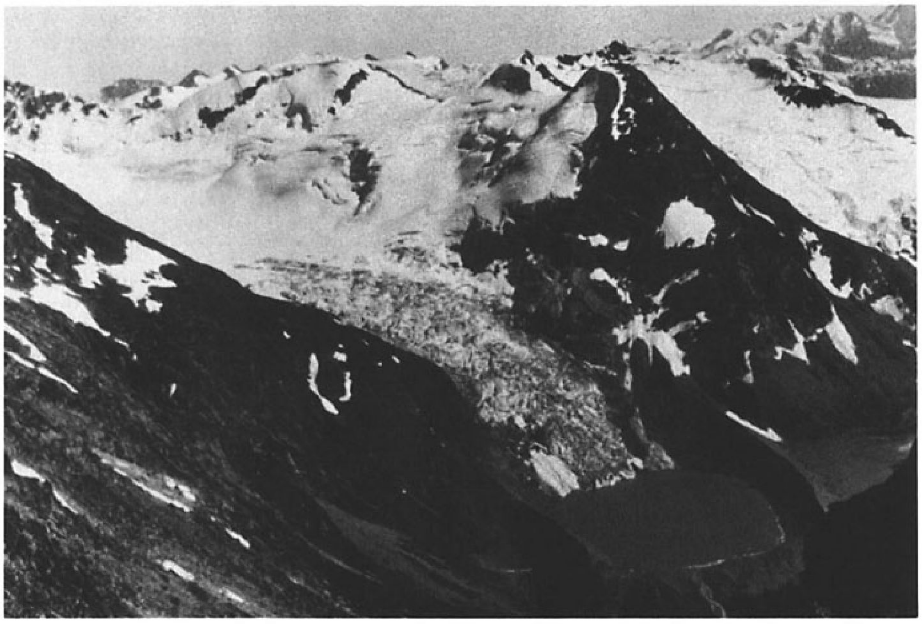


Figure 10A. Photograph of Nostetuko Lake, a neoglacial moraine-dammed lake, 1977. (Photograph by J. M. Ryder, courtesy of Michael Church, University of British Columbia.)

Figure 10B. Photograph of Nostetuko Lake and Cumberland Glacier, British Columbia, Canada, in August 1983, after failure of the moraine dam. Cross section of dam shown in Figure 13. (Photograph by Michael Church, University of British Columbia.)

than 10 m (Plafker and Eyzaguirre, 1979). Another failure mechanism is overtopping and breaching by excessive runoff during glacial retreat, snowmelt, or intense rainfall. The moraine dam impounding Lago Tempanos, Argentina, failed sometime between 1942 and 1953 because of excessive melt water accompanying a 352-m retreat of the glacier (Rabassa and others, 1979). In the Cordillera Blanca, Peru, all precisely dated moraine-dam failures occurred during the rainy season from October to April (Lliboutry and others, 1977). Failure during these wet months indicates that increased stream flow is an important factor in some moraine-dam failures.

Settlement and subsequent failure of moraine dams accompanying earthquakes is another potential failure mechanism. The large Peruvian earthquake of May 1970 resulted in the release of water by piping from at least two moraine-dammed lakes in the Cordillera Blanca (Lliboutry and others, 1977).

A moraine dam in the Soviet Union collapsed from melting of frozen soil because of high air and water temperatures (Yesenov and Degovets, 1979). Although we know of no well-documented case, the failure of an ice-cored moraine dam from ice melt also is a distinct possibility (Buchroithner and others, 1982).

Longevity and Control of Moraine Dams

The question of the longevity and stability of moraine dams is extremely complex. In our investigations, all of the known moraine dams that failed were late-neoglacial age or younger. Because ice or rock avalanches into moraine-dammed lakes are the primary failure mechanism of moraine dams, lakes located below steep, unstable, highly crevassed or fractured glaciers or rock slopes present obvious failure potential. In a study of the hypothetical failure and resulting flood from a late-neoglacial moraine dam in central Oregon, the annual probability of failure was estimated to be 1% to 5% because of the instability of the surrounding rock slopes and glacier and the history of previous moraine-dam failures in the area (Laenen and others, 1987). Ice-cored moraines or frozen-soil moraines may thaw for centuries and then become critically unstable (Ostrem, 1964; Andrews, 1975). Once this occurs, the potential for a piping or overtopping failure of the moraine dam increases whenever a period of high runoff occurs.

Artificial controls of the levels of moraine-dammed lakes have been attempted in several locations. The most extensive efforts probably have been undertaken in Peru (Lliboutry and others, 1977). Control efforts include draining of lakes by tunnels through ice and rock, stabilization of lake outlets with paved revetments, increasing freeboard with low earthen dams, and construction of protective retention basins if valley gradients are sufficiently low (Lliboutry and others, 1977; Yesenov and Degovets, 1979; Eisbacher, 1982).

FLOODS FROM THE FAILURE OF NATURAL DAMS

Natural dams create the potential for two very different types of flooding, (1) upstream or backwater flooding as the reservoir fills and

(2) downstream flooding as a result of failure of the dam.

Upstream flooding occurs because of the relatively slow rise of water behind the dam as the basin of the natural impoundment is filled. The threat of loss of life from this kind of flooding is minimal, but property damage can be substantial. Upstream flood damage from glacier and moraine dams generally is not significant because these types of natural dams commonly occur in remote areas where development is minimal. Landslide dams, however, can present significant hazards from backwater flooding. Because landslide dams tend to occur in mountainous areas, certain types of structures, such as hydroelectric plants, may be rendered inoperable because of inundation of intakes, flumes, generators, and transportation and transmission facilities (Schuster and Costa, 1986b). A recent example of the consequences of upstream flooding from a landslide dam occurred in April 1983, when a 22 million-m^3 landslide in central Utah dammed the Spanish Fork River and flooded the town of Thistle, Utah (Kaliser and Fleming, 1986) (Fig. 11).

It usually is possible to accurately estimate the extent and rate of upstream flooding from natural dams. Such estimates require knowledge of height of the dam crest, rates of stream flow or icemelt into the natural reservoir, rates of seepage through or beneath the dam, and information on topography upstream from the dam.

Figure 11. Photograph of the 1983 Thistle, Utah, landslide (right) and its temporary impoundment, Thistle Lake (left), in September 1983. The lake inundated the town of Thistle and was then drained late in 1983 by a bedrock tunnel constructed through the mountain at lower left.

TABLE 6. SUMMARY OF REGRESSION EQUATIONS TO PREDICT PEAK DISCHARGE FROM THE FAILURE OF EARTH- AND ROCK-FILL, LANDSLIDE, MORAINE, AND GLACIER DAMS

Type of dam	Equation	Number of data points	Coefficient of determination (r^2)	Standard error (%)
1. Earth- and rock-fill	$Q = 0.0184(PE)^{0.42}$	26	0.75	91
2. Landslide	$Q = 0.0158(PE)^{0.41}$	12	0.81	185
3. Moraine	$Q = 0.00013(PE)^{0.60}$	8	0.78	92
4. Glacier	$Q = 0.0000055(PE)^{0.59}$	11	0.80	64

Note: Q = peak discharge (m^3/s); PE = potential energy (joules).

Comparison of Floods from the Failure of Different Kinds of Dams

Floods resulting from the failure of natural dams in most cases are much larger than floods originating directly from snowmelt or rainfall. Compared with the failure of constructed dams, very little is known about the processes of natural-dam failure. Few accurate data exist about peak discharges, dimensions, or reservoir volumes of failed natural dams (Costa, 1985).

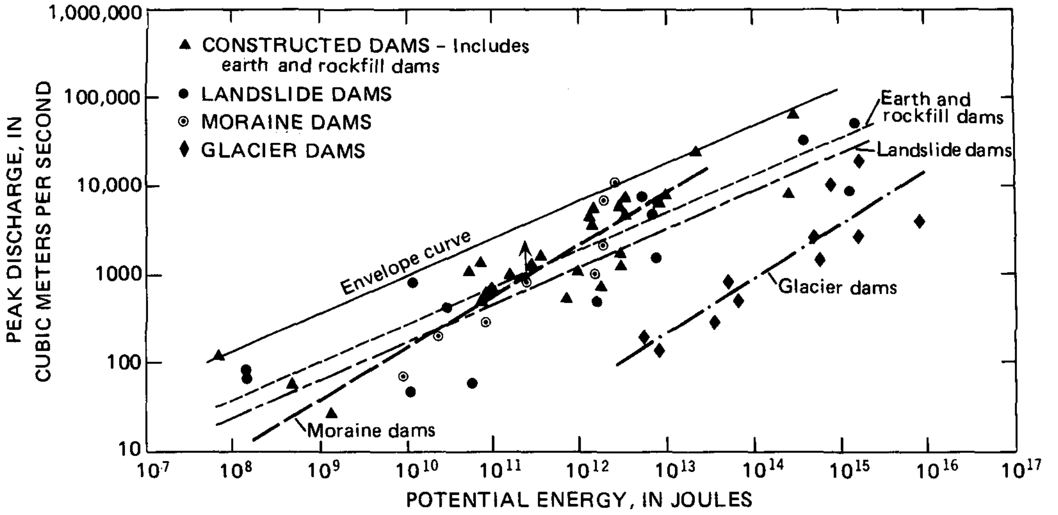
Many investigations have been conducted on the safety of constructed dams (Jansen, 1980; Committee on the Safety of Existing Dams, 1983), and numerous models have been proposed to determine the outflow hydrographs and downvalley routing of flood waters resulting from failure of constructed dams (Fread, 1980; Land, 1980). Few similar evaluations, however, have been made for the failures of natural dams (Ponce and Tsivoglou, 1981; Clarke, 1982), which in many cases, are different from those of constructed dams (Costa, 1985).

A dam failure is a complex hydrologic, hydraulic, and geologic phenomenon, controlled primarily by the failure mechanism and characteristics and properties of the dam. One way to compare different kinds of dam failures is to investigate the relationship between the potential energy of the lake water behind the dam prior to failure and the flood peak discharge from the failure of the dam (Fig. 12). Potential energy of a lake behind a dam can be computed as the product of dam height (metres), volume (cubic metres), and specific weight of water (9,800 newtons/cubic metre). Dam-failure flood peak discharges used in Figure 12 come from Tables 2, 3, and 5 and from Costa (1985).

Regression analysis with potential energy as the independent variable produces different equations for landslide, glacier, moraine, and earth- and rock-fill dam-failure flood peaks, with standard errors ranging from 64% for glacier dams to 185% for landslide dams (Table 6). The large scatter in the data in Figure 12 reflects the diverse characteristics of individual dams within each category, as well as the difficulty in computing or measuring the peak discharge from a dam failure. Direct measurements of floods are nearly impossible; thus, a variety of indirect estimation methods, such as drawdown rates or measurements based on post-flood channel surveys and hydraulic formulas, are used. Concern about the large standard errors, or overlapping of data from different types of dams, is moot because the variability of individual dam populations is so large and determination of the dependent variable (peak discharge) is so difficult. Individual regression lines identify different kinds of dams in a physically meaningful way that provides insight into fundamental understanding of natural dams.

For the same potential energy at the time of dam failure, glacier dams produce the smallest peak discharges. For potential energy less than about 10^{11} joules, constructed earth- and rock-

Figure 12. Graph showing potential energy of lake water versus peak discharge for various types of dam failures. Dashed lines are least-squares regression lines for different kinds of dams. Solid line is the envelope curve for all dam-failure data. Data from Costa (1985) and Tables 2, 3, and 5.



fill dams produce the largest peak discharges for a constant potential energy. For potential energy greater than about 10^{11} to 10^{12} joules, moraine-dam failures produce the largest peak discharges for a constant potential energy. Differences in peak discharges for constant potential energy of different kinds of natural and constructed dams originate partly because of differences in failure mechanisms, which are related to geometry and to material characteristics of the dams (Table 7).

Glacier-dam failures commonly involve the enlargement of subglacial or englacial tunnels during failure. This enlargement requires time and produces relatively small peak discharges compared to discharges from other kinds of natural and constructed dams with the same potential energy. This is not always the case. The recent advance of Hubbard Glacier into Russell Fiord, Alaska, dammed the fiord and formed Russell Lake. The ice dam failed, and a very large flood peak (104,000 m^3/s) resulted for the potential energy of the lake (1.3×10^{15} joules) (Seitz and others, 1986). This is because the Hubbard Glacier was basically different from most glacier dams and acted as a brittle structure. Rising water levels in Russell Lake eventually swept away a piece of the dam, and the dam failed much more quickly than most glacier dams.

Landslide dams are typically much wider than constructed earth- and rock-fill dams and involve much larger volumes of material. A landslide dam that is implaced dynamically will have a much greater volume than a constructed embankment dam of the same height because the slopes will be flatter. The Madison Canyon landslide (Fig. 7) that dammed the Madison River in 1959, forming Earthquake Lake, had a base width five to eight times as great as would have been used in building a rock-fill dam of the same height (Knight and Bennett, 1960). Transverse sections of the Mayunmarca landslide dam, Peru, and the Nostetuko moraine dam, British Columbia, are compared to that of the Oroville Dam, a large earth-fill dam in California, in Figure 13. The landslide dam in Peru is nearly as high as the constructed dam but is more than three times as wide. When a landslide dam is overtopped, much more earth material commonly is present for water to erode before a full breach is developed than is the case for constructed embankment dams. Data from Figure 12 and Table 6, however, indicate that on average, flood peak discharges from earth- and rock-fill dam failures are only 15%–20% greater than flood peaks from landslide dams with the same potential energy, in spite of the larger volume of material to be breached. This may imply that landslide-dam sediment is inherently more "erodible" than constructed embankment dam material.

Moraine dams are relatively high and narrow, compared to many landslide dams, and have much steeper slopes. The predominant failure mechanism for moraine dams (wave overtopping followed by breaching) leads to rapid erosion of cohesionless sandy and gravelly till comprising many moraine dams (Costa, 1987). The rapid breach development in moraine-dam failures compared to that of other kinds of dams is primarily responsible for the location of the regression line in Figure 12.

Prediction and Reconstruction of Floods from Dam Failures

For purposes of rapid prediction when potential loss of life or property is involved, a conservative peak-discharge estimate based on an envelope curve developed from historic failures of landslide, glacier, moraine, and constructed earth- and rock-fill dams can be made from knowledge of the potential energy of the lake behind the dam (Fig. 12). The envelope curve that includes data points from all constructed-

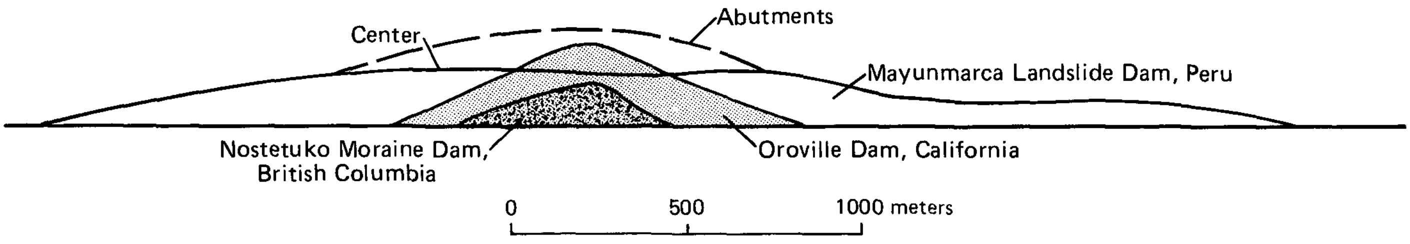


Figure 13. Cross section of Mayunmarca landslide dam, Peru, and Nostetuko moraine dam, British Columbia, compared to the maximum cross section of a large constructed earth-fill dam at Oroville, California. (Modified from Lee and Duncan, 1975.)

TABLE 7. PREDOMINANT FAILURE MECHANISMS OF CONSTRUCTED AND NATURAL DAMS

Type of dam	Predominant failure mechanism
Constructed (earth- and rock-fill)	Piping and seepage
	Overtopping
	Foundation
Glacier	Progressive enlargement of tunnels and channels
	Hydrostatic flotation
Landslide	Overtopping
Moraine	Wave overtopping

and natural-dam failures for which reasonable estimates of peak discharge exist is defined by the equation

$$Q = 0.063\ PE^{0.42},$$

where Q is peak discharge, in cubic metres per second, and PE is potential energy, in joules.

For reconstructing past flood peaks from the failure of natural dams for paleohydrological or sedimentological investigations, regression equations for different kinds of natural dams with potential energy as the independent variable could be used (Table 6).

A complicating factor in downstream routing of floods from natural-dam failures is the bulking and debulking of flood waters with sediment and debris as the flood moves downvalley. The use of envelope curves, regression equations, or dam-break models allows estimation of peak flood discharges at the dam. Most commonly, flood peak discharges attenuate downvalley (Costa, 1985, Fig. 8). Sometimes, however, downstream peaks can be considerably larger because easily eroded sediment is incorporated into the flow. So much sediment can be added to the flood flow that a debris flow forms. This seems to be an especially important process in volcanic and glacial terrains (Lliboutry and others, 1977; Yesenov and Degovets, 1979; Clague and others, 1985; Scott, 1985). Fluctuations in peak discharge downstream from the failure of a moraine dam on the Kumbel River, U.S.S.R., in 1977, are well documented. Peak discharge from the dam failure was 210 m^3/s, but it had bulked to 11,000 m^3/s about 15 km downstream (Yesenov and Degovets, 1979). This problem of bulking and debulking of flood flows represents a difficult unsolved problem in sediment transport today, and its consequences for hazard evaluation are significant.

CONCLUSIONS

Three kinds of natural dams present significant hazards to large numbers of people and to property: landslide dams, glacier dams, and moraine dams. Given a large data base of case studies, significant generalizations about individual kinds of natural dams can be made. Landslide dams form most commonly in steep narrow valleys in geologically active areas, but they have also formed in wide, open stream valleys. Avalanches, slumps and slides, and flows triggered by excessive snowmelt or rainfall, or earthquakes, are the most common landslide processes. There are at least six morphologically different kinds of landslide dams, and the danger of failure and flooding varies with the kind of landslide dam.

On the basis of 73 examples of landslide-dam failures from around the world, landslide dams fail quickly after formation (half failed within 10 days of formation, and only 15% last more than a year). By far the predominant failure mechanism is overtopping and breaching by headward stream erosion.

Glacier-dam failures have produced the largest documented historic and prehistoric flood-peak discharges known on Earth. The most dangerous glacier dams form when tributary-valley glaciers block main valleys and form large lakes behind them. Temperate glacier dams in most cases fail by erosion of subglacial or englacial openings under or through the ice dam, aided by the hydrostatic pressure of water behind the ice dam. Cold polar-ice dams fail most commonly by overtopping and erosion of channels in the ice.

All the documented cases of moraine-dam failures occurred for moraine dams formed in the last few centuries (late-neoglacial age). The dams originated as dump or ice-thrust moraines and may or may not have ice cores. The predominant failure mechanism is overtopping and rapid erosion by a wave or series of waves generated by rock or ice avalanches into the lake from adjacent steep cirque and valley walls.

For the same potential energy at the dam site, the failures of glacier dams produce the smallest flood peak discharges because of the time required for enlargement of outlet tunnels and channels. For constant potential energy, landslide-dam failures produce smaller flood peaks than do the failures of constructed earth- and rock-fill dams because of the large volume of material to be eroded before full breach development. This occurs in spite of the fact that landslide-dam sediment may be inherently more erodible than constructed earth- and rock-fill dams. For potential energy greater than about 10^{11} to 10^{12} joules, late-neoglacial moraine dams produce the greatest flood peak discharges of any kind of natural or earth- or rock-fill dam because of rapid breach formation associated with wave overtopping and erosion of noncohesive till on extremely steep slopes.

An envelope curve defining the maximum discharge produced by the failure of natural and constructed earth- and rock-fill dams can be used as a rapid conservative approximation of the flood peak from the failure of a potentially dangerous natural dam. In areas with abundant loosely consolidated surficial deposits in stream valleys downstream of natural dams that may fail, peak discharge may not attenuate but can actually increase manyfold by incorporation of easily erodible sediment and debris. This phenomenon of sediment bulking and debulking downstream from natural-dam failures remains one of the most pressing unresolved problems in flood-hazard investigations.

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REFERENCES CITED

Adams, John, 1981, Earthquake-dammed lakes in New Zealand: Geology, v. 9, p. 215–219.

Aitkenhead, N., 1960, Observations on the drainage of a glacier-dammed lake in Norway: Journal of Glaciology, v. 3, p. 607–609.

Alden, W. C., 1928, Landslide and flood at Gros Ventre, Wyoming: American Institute of Mining and Metallurgical Engineers Transactions, v. 76, p. 347–358.

Anderson, G. P., 1948, Waikaremoana—The problem of lake control: New Zealand Institute of Engineers Proceedings, v. 34, p. 508–526.

Andrews, J. T., 1975, Glacial systems: North Scituate, Massachusetts, Duxbury Press, 191 p.

Arnborg, L., 1955, Hydrology of the glacial river Austurfljot: Geografiska Annaler, v. 36, part 3–4, p. 185–201.

Baker, V. R., 1973, Paleohydrology and sedimentology of Lake Missoula flooding in eastern Washington: Geological Society of America Special Paper 144, 79 p.

Ballantyne, C. K., and McCann, S. B., 1980, Short-lived damming of a high-Arctic ice-marginal stream, Ellesmere Island, N.W.T., Canada: Journal of Glaciology, v. 25, p. 487–491.

Berg, L. S., 1950, Natural regions of the U.S.S.R.: New York, Macmillan Co., 435 p.

Blachut, S. P., and Ballantyne, C. K., 1976, Ice-dammed lakes—A critical review of their nature and behavior: Hamilton, Ontario, McMaster University Department of Geography Discussion Paper 6, 90 p.

Blown, Iain, and Church, Michael, 1985, Catastrophic lake drainage within the Homathko River basin, British Columbia: Canadian Geotechnical Journal, v. 22, no. 4, p. 551–563.

Bradley, W. C., Fahnestock, R. K., and Rowekamp, E. T., 1972, Coarse sediment transport by flood flows on Knik River, Alaska: Geological Society of America Bulletin, v. 83, p. 1261–1284.

Bretz, J H., Smith, H.T.U., and Neff, G. E., 1956, Channeled scablands of Washington: New data and interpretations: Geological Society of America Bulletin, v. 67, p. 957–1049.

Buchroithner, M. F., Jentsch, G., and Wanivenhaus, B., 1982, Monitoring of recent geological events in the Khumbu area (Himalaya, Nepal) by digital processing of Landsat MSS data: Rock Mechanics, v. 15, p. 181–197.

Budd, W. F., 1975, A first simple model for periodically self-surging glaciers: Journal of Glaciology, v. 14, p. 3–21.

Burgisser, H. M., Gansser, A., and Pika, J., 1982, Late glacial lake sediments of the Indus Valley area, northwestern Himalayas: Ecologae Geologica Helvetae, v. 75, p. 51–63.

Butler, D. R., Oelfke, J. G., and Oelfke, L. A., 1986, Historic rockfall avalanches, northeastern Glacier National Park, Montana, U.S.A.: Mountain Research and Development, v. 6, p. 1–11.

Chang, Longchian, 1934, Investigation of the Deixi Earthquake, Sichuan: The Geological Society of China, Nanking, China, Comments on Geology, v. 3, no. 3, p. 251–292 [in Chinese].

Chang, S. C., 1984, Tsao-Ling landslide and its effect on a reservoir project: International Symposium on Landslides, 4th, Toronto, September 16–21, Proceedings, v. 1, p. 469–473.

Church, Michael, 1972, Baffin Island sandurs—A study of Arctic fluvial processes: Geological Society of Canada Bulletin 216, 208 p.

Clague, J. J., and Mathews, W. H., 1973, The magnitude of jökulhlaups: Journal of Glaciology, v. 12, p. 501–504.

Clague, J. J., Evans, S. G., and Blown, I. G., 1985, A debris flow triggered by the breaching of a moraine-dammed lake, Klattasine Creek, British Columbia: Canadian Journal of Earth Sciences, v. 22, p. 1492–1502.

Clark, T. H., 1947, Two recent landslides in Quebec: Transactions of the Royal Society of Canada, v. 41, ser. 3, sec. 4, p. 9–18.

Clarke, G.K.C., 1982, Glacier outburst floods from "Hazard Lake," Yukon Territory, and the problem of flood magnitude prediction: Journal of Glaciology, v. 28, p. 3–21.

Clarke, G.K.C., and Waldron, D. A., 1984, Simulation of the August 1979 sudden discharge of glacier-dammed Flood Lake, British Columbia: Canadian Journal of Earth Sciences, v. 21, p. 502–504.

Clarke, G.K.C., Mathews, W. H., and Pack, R. T., 1984, Outburst floods from Glacial Lake Missoula: Quaternary Research, v. 22, p. 289–299.

Clement, Paul, 1984, The drainage of a marginal ice-dammed lake at Nordbogletscher, Johan Dahl Land, South Greenland: Arctic and Alpine Research, v. 16, p. 209–216.

Committee on the Safety of Existing Dams, 1983, Safety of existing dams, evaluation and improvement: Washington, D.C., National Academy Press, 354 p.

Costa, J. E., 1985, Floods from dam failures: U.S. Geological Survey Open-File Report 85-560, 54 p.

——— 1987, Flood hazards of moraine-dam failures: Geological Society of America Abstracts with Programs, v. 19, no. 7, p. 628.

Cotecchia, V., 1978, Systematic reconnaissance mapping and registration of slope movements: International Association of Engineering Geology Bulletin, v. 17, p. 5–37.

Cotton, C. A., 1941, Landscape, as developed by the processes of normal erosion: New York, John Wiley & Sons, Inc., 509 p.

Crandell, D. R., and Varnes, D. J., 1961, Movement of the Slumgullion earthflow near Lake City, Colorado: U.S. Geological Survey Professional Paper 424-B, p. B-136–B-139.

Davis, W. M., 1882, On the classification of lake basins: Boston Society of Natural History Proceedings, v. 21, p. 315–381.

——— 1933, The lakes of California: California Journal of Mines and Geology, v. 29, p. 175–236.

Dawson, G. M., 1898, Remarkable landslip in Portneuf County, Quebec: Geological Society of America Bulletin, v. 10, p. 484–490.

Eisbacher, G. H., 1982, Mountain torrents and debris flows: Episodes, v. 1982, no. 4, p. 12–17.

Eisbacher, G. H., and Clague, J. J., 1984, Destructive mass movements in high mountains—Hazard and management: Geological Survey of Canada Paper 84-16, 230 p.

Emerson, F. B., 1925, 180-ft. dam formed by landslide in Gros Ventre Canyon: Engineering News-Record, v. 95, no. 12, p. 467–468.

Ericksen, G. E., Plafker, George, and Concha, J. F., 1970, Preliminary report on the geologic events associated with the May 31, 1970, Peru earthquake: U.S. Geological Survey Circular 639, 25 p.

Evans, S. G., 1984, The 1880 landslide dam on Thompson River near Ashcroft, British Columbia, *in* Current research: Geological Survey of Canada, Paper 84-1A, Part A, p. 655–658.

Finch, R. H., 1937, A tree-ring calendar for dating volcanic events, Cinder Cone, Lassen National Park, California: American Journal of Science, v. 33, p. 140–146.

Fread, D. L., 1980, DAMBRK—The NWS dam-break flood forecasting model: Silver Spring, Maryland, National Weather Service, Office of Hydrology, 37 p.

——— 1985, BREACH—An erosion model for earthen dam failures: Silver Spring, Maryland, National Weather Service, 29 p.

Fushimi, H., Ikegami, K., Higuchi, K., and Shankar, K., 1985, Nepal case study: Catastrophic floods, *in* Young, G. J., ed., Techniques for prediction of runoff from glacierized areas: International Association of Hydrological Sciences Publication 149, p. 125–130.

Galay, V. J., 1985, Hindu Kush–Himalayan erosion and sedimentation in relation to dams: Chinese Academy of Science, International Workshop on Water Management in the Hindu Kush–Himalaya region, Chengdu, China, 24 p.

Gallino, G. L., and Pierson, T. C., 1985, Polallie Creek debris flow and subsequent dam-break flood of 1980, East Fork Hood River basin, Oregon: U.S. Geological Survey Water Supply Paper 2273, 22 p.

Gasiev, E., 1984, Study of the Usoy landslide in Pamir: International Symposium on Landslides, 4th, Toronto, Canada, September 16–21, 1984, Proceedings, v. 1, p. 511–515.

Geist, J. M., and Schuster, R. L., 1986, Hole-in-the-Wall Gulch landslide, Baker County, Oregon: Symposium on Engineering Geology and Soils Engineering, 22nd, Boise, Idaho, Proceedings, p. 227–244.

Gilbert, G. K., 1878, The ancient outlet of Great Salt Lake: American Journal of Science, v. 15, p. 256–259.

Gilbert, R., 1971, Observations on ice-dammed Summit Lake, British Columbia, Canada: Journal of Glaciology, v. 10, p. 351–356.

Glazyrin, G. Ye., Reyzvikh, V. N., 1968, Computation of the flow hydrograph for the breach of landslide lakes: Soviet Hydrology, no. 5, p. 592–596.

Grove, J. M., 1979, The glacial history of the Holocene: Progress in Physical Geography, v. 3, p. 1–54.

Gunn, J. P., 1930, The Shyok flood, 1929: The Himalayan Journal, v. 2, p. 35–47.

Hadley, J. B., 1964, Landslides and related phenomena accompanying the Hebgen Lake earthquake of August 17, 1959: U.S. Geological Survey Professional Paper 435, p. 107–138.

Haeberli, Wilfried, 1983, Frequency and characteristics of glacier floods in the Swiss Alps: Annals of Glaciology, v. 4, p. 85–90.

Harp, E. L., Wilson, R. C., and Wieczorek, G. F., 1981, Landslides from the February 4, 1976, Guatemala earthquake: U.S. Geological Survey Professional Paper 1204-A, 35 p.

Harrison, A., 1974, Madison Canyon slide mass modification by the U.S. Army Corps of Engineers, *in* Voight, Barry, ed., Rock mechanics—The American Northwest: International Society for Rock Mechanics, International Congress on Rock Mechanics, 3rd, Pennsylvania State University College of Earth Sciences Experiment Station Special Publication, p. 138–143.

Hewitt, Kenneth, 1982, Natural dams and outburst floods of the Karakoram Himalaya, *in* Glen, J. W., ed., Hydrological aspects of alpine and high-mountain areas: International Association of Hydrological Sciences Publication 138, p. 259–269.

Holmes, Arthur, 1965, Principles of physical geology (2nd edition): New York, Ronald Press, 1,288 p.

Hutchinson, G. E., 1957, A treatise on limnology, Volume 1: New York, John Wiley & Sons, 1,015 p.

Hutchinson, J. N., and Kojan, E., 1975, The Mayunmarca landslide of 25 April 1974: UNESCO Serial 3124/RHO. RD/SCE, Paris, 23 p.

Jansen, R. B., 1980, Dams and public safety: Denver, Colorado, U.S. Department of the Interior, Bureau of Reclamation, 332 p.

Jones, D. P., Ricker, K. E., DeSloges, J. R., and Maxwell, Michael, 1985, Glacier outburst flood on the Noeick River—The draining of Ape Lake, British Columbia, October 20, 1984: Geological Survey of Canada Open-File Report 1139, 81 p.

Kaliser, B. N., and Fleming, R. W., 1986, The 1983 landslide dam at Thistle, Utah, *in* Schuster, R. L., ed., Landslide dams: Processes, risk, and mitigation: American Society of Civil Engineers Geotechnical Special Publication 3, p. 59–83.

King, W.D.V.O., 1934, The Mendoza River flood of 10–11 January 1934, Argentina: Geographical Journal, v. 84, p. 321–326.

Knight, D. K., and Bennett, P. T., 1960, Stability of slide dam and recommendations on development of overflow spillway, *in* Madison River, Montana, report on flood emergency, Madison River slide: U.S. Army Corps of Engineers, Riverdale, North Dakota, Appendix VI, 5 p.

Laenen, Antonius, Scott, K. M., Costa, J. E., and Orzol, L. L., 1987, Hydrologic hazards along Squaw Creek from a hypothetical failure of the glacial moraine impounding Carver Lake near Sisters, Oregon: U.S. Geological Survey Open-File Report 87-41, 48 p.

Land, L. F., 1980, Evaluation of selected dam-break floodway models by using field data: U.S. Geological Survey Water-Resources Investigations Report 80-44, 54 p.

Lee, K. L., and Duncan, J. M., 1975, Landslide of April 25, 1974, on the Mantaro River, Peru: Washington, D.C., Committee on Natural Disasters, Commission on Sociotechnical Systems, National Research Council, 72 p.

Li Tianchi, Schuster, R. L., and Wu Jishan, 1986, Landslide dams in south-central China, *in* Schuster, R. L., ed., Landslide dams—Processes, risk, and mitigation: American Society of Civil Engineers Geotechnical Special Publication 3, p. 146–162.

Lliboutry, Louis, Arnao, B. M., Pautre, Andre, and Schneider, Bernard, 1977, Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru. I. Historical failures of morainic dams, their causes and prevention: Journal of Glaciology, v. 18, p. 239–254.

Maag, H. V., 1969, Ice-dammed lakes and marginal glacial drainage on Axel Heiberg Island: McGill University, Montreal, Axel Heiberg Island Research Report, 147 p.

Malde, H. E., 1968, The catastrophic late Pleistocene Bonneville flood in the Snake River plain, Idaho: U.S. Geological Survey Professional Paper 596, 52 p.

Marcus, M. G., 1960, Periodic drainage of glacier-dammed Tulsequah Lake, British Columbia: Geographical Review, v. 50, p. 89–106.

Marr, J. E., 1916, The geology of the Lake District and the scenery as influenced by geological structure: Cambridge University Press, 220 p.

Mason, Kenneth, 1929, Indus floods and Shyok glaciers: The Himalayan Journal, v. 1, p. 10–29.

Mathews, W. H., 1965, Two self-dumping ice-dammed lakes in British Columbia: Geographical Review, v. 55, p. 46–52.

Matthes, F. E., 1939, Report of Committee on Glaciers: American Geophysical Union Transactions, v. 20, p. 518–523.

Meier, M. A., and Post, Austin, 1969, What are glacier surges?: Canadian Journal of Earth Science, v. 6, p. 807–817.

Meyer, W., Sabol, M. A., and Schuster, R. L., 1986, Landslide dammed lakes at Mount St. Helens, Washington, *in* Schuster, R. L., ed., Landslide dams—Processes, risk, and mitigation: American Society of Civil Engineers Geotechnical Special Publication 3, p. 21–41.

Nash, D.F.T., Brunsden, D. K., Hughes, R. E., Jones, D.K.C., and Whalley, B. F., 1985, A catastrophic debris flow near Gupis, northern areas, Pakistan: International Conference on Soil Mechanics and Foundation Engineering, 11th, San Francisco, 12–16 August, Proceedings, v. 3, p. 1163–1166.

Nichols, R. L., and Miller, M. M., 1952, The Moreno Glacier, Lago Argentino, Patagonia, advancing glaciers and nearby simultaneously retreating glaciers: Journal of Glaciology, v. 2, p. 41–50.

Nolf, Bruce, 1966, Broken Top breaks—Flood released by erosion of glacial moraine: The Ore Bin, v. 28, no. 10, p. 182–188.

Nye, J. F., 1976, Water flow in glaciers—Jökulhlaups, tunnels, and veins: Journal of Glaciology, v. 17, p. 181–207.

Ostrem, G., 1964, Ice-cored moraines in Scandinavia: Geografiska Annaler, v. 46, p. 282–337.

Ousley, Ralph, 1788, An account of the moving of a bog, and the formation of a lake, in the county of Galway, Ireland: Transactions of the Royal Irish Academy, v. 2, p. 3–5.

Plafker, George, and Eyzaguirre, V. R., 1979, Rock avalanche and wave at Chungar, Peru, *in* Voight, Barry, ed., Rockslides and avalanches, 2: Amsterdam, the Netherlands, Elsevier, p. 269–279.

Ponce, V. M., and Tsivoglou, A. J., 1981, Modeling gradual dam breaches: Hydraulics Division Journal, American Society of Civil Engineers, v. 106, no. HY7, p. 829–838.

Porter, S. C., and Denton, G. H., 1967, Chronology of neoglaciation in the North American Cordillera: American Journal of Science, v. 267, p. 177–210.

Post, Austin, and Mayo, L. R., 1971, Glacier dammed lakes and outburst floods in Alaska: U.S. Geological Survey Hydrologic Investigations Atlas HA-455, 10 p.

Pushkarenko, V. P., 1982, Regularities of mud-rock flow formation in central Asia, *in* Sheko, A., ed., Landslides and mudflows: Centre of International Projects, GKNT, Moscow, U.S.S.R., Alma-Ata International Seminar, October 1981, Reports, p. 87–106.

Rabassa, Jorge, Rubulis, S., and Suarez, J., 1979, Rate of formation and sedimentology of (1976–1978) push-moraines, Frias Glacier, Mount Tronadoz (41°10′ S; 71°53′ W), Argentina, *in* Schluchter, Ch., ed., Moraines and varves: Rotterdam, the Netherlands, A. A. Balkema, p. 65–79.

Richardson, Donald, 1968, Glacier outburst floods in the Pacific Northwest: U.S. Geological Survey Professional Paper 600-D, p. D79–D86.

Rosengren, N., 1984, Sites of geological and geomorphological significance in the shire of Otway: Victoria (Australia) Department of Conservation, Forests, and Lands E.S.P. 399, p. 107–111.

Russell, I. C., 1893, A geological reconnaissance in central Washington: U.S. Geological Survey Bulletin 108, 168 p.

Sager, J. W., and Chambers, D. R., 1986, Design and construction of the Spirit Lake outlet tunnel, Mount St. Helens, Washington, *in* Schuster, R. L., ed., Landslide dams—Processes, risk, and mitigation: American Society of Civil Engineers Geotechnical Special Publication 3, p. 42–58.

Schuster, R. L., 1985, Landslide dams in the western United States: International Conference and Field Workshop on Landslides, 4th, Tokyo, Proceedings, p. 411–418.

Schuster, R. L., and Costa, J. E., 1986a, A perspective on landslide dams, *in* Schuster, R. L., ed., Landslide dams—Processes, risk, and mitigation: American Society of Civil Engineers Geotechnical Special Publication 3, p. 1–20.

——— 1986b, Effects of landslide damming on hydroelectric projects: International Congress of the International Association of Engineering Geology, 5th, Buenos Aires, Argentina, Proceedings, v. 4, p. 1295–1307.

Scott, K. M., 1985, Lahars and lahar-runout flows in the Toutle-Cowlitz River system, Mount St. Helens, Washington—Origins, behavior, and sedimentology: U.S. Geological Survey Open-File Report 85-500, 202 p.

Scott, W. E., Meloy, W. D., Shroba, R. R., and Miller, R. D., 1980, New interpretations of the late Quaternary history of Lake Bonneville, western United States: American Quaternary Association Abstracts with Programs, v. 6, p. 168.

Seitz, H. R., Thomas, D. S., and Tomlinson, B., 1986, The storage and release of water from a large glacier-dammed lake: Russell Lake near Yakutat, Alaska, 1986: U.S. Geological Survey Open-File Report 86-545, 10 p.

Sherard, J. L., 1979, Sinkholes in dams of coarse, broadly grained soils: International Congress on Large Dams, 13th, New Delhi, India, Transactions, v. 2, p. 25–35.

Silva, L., Cocheme, J. J., Canul, R., Duffield, W. A., and Tilling, R. I., 1982, The March–April 1982 eruptions of Chichonal Volcano, Chiapas, Mexico—Preliminary observations [abs.]: EOS (American Geophysical Union Transactions), v. 63, p. 1126.

Snow, D. T., 1964, Landslide of Cerro Condor–Sencca, Department of Ayacucho, Peru, *in* Kiersch, G. A., ed., Engineering geology case histories: Geological Society of America, no. 5, p. 1–6.

Stone, K. H., 1963, The annual emptying of Lake George, Alaska: Arctic, v. 16, p. 26–40.

Sturm, Matthew, and Benson, C. S., 1985, A history of jökulhlaups from Strandline Lake, Alaska, U.S.A.: Journal of Glaciology, v. 31, p. 272–280.

Sugden, D. E., and John, B. S., 1976, Glaciers and landscape: London, United Kingdom, Halsted Press, 376 p.

Sugden, D. E., Clapperton, C. M., and Knight, P. G., 1985, A jökulhlaup near Sondre Stromfjord, West Greenland, and some effects on the ice-sheet margin: Journal of Glaciology, v. 31, p. 366–368.

Swanson, F. J., Graham, R. L., and Grant, G. E., 1985, Some effects of slope movements on river channels, *in* International Symposium on Erosion, Debris Flow, and Disaster Prevention, Proceedings: Tsukuba, Japan, Erosion Control Engineering Society of Japan, p. 273–278.

Swanson, F. J., Oyagi, Norio, and Tominaga, Masaki, 1986, Landslide dams in Japan, *in* Schuster, R. L., ed., Landslide dams—Processes, risk, and mitigation: American Society of Civil Engineers Geotechnical Special Publication 3, p. 131–145.

Thorarinsson, Sigurdur, 1939, The ice-dammed lakes of Iceland with particular reference to their value as indicators of glacial oscillations: Geografiska Annaler, v. 21, no. 3–4, p. 216–242.

——— 1953, Some new aspects of the Grimsvotn problem: Journal of Glaciology, v. 2, p. 267–275.

——— 1957, The jökulhlaup from the Katla area in 1955 compared with other jökulhlaups in Iceland: Reykjavik, Museum of National History Miscellaneous Paper 18, p. 21–25.

Tufuell, Lance, 1984, Glacier hazards: London, United Kingdom, Longman, 97 p.

U.S. Bureau of Reclamation, 1974, Design of small dams (2nd edition): Washington, D.C., U.S. Government Printing Office, 816 p.

Varnes, D. J., 1978, Slope movement types and processes, *in* Schuster, R. L., and Krizek, R. J., eds., Landslides—Analysis and control: National Academy of Sciences, Washington, D.C., Transportation Research Board Special Report 176, p. 11–33.

Vuichard, Daniel, and Zimmermann, Markus, 1987, The 1985 catastrophic drainage of a moraine-dammed lake, Khumbu Himal: Cause and consequences: Mountain Research and Development, v. 7, p. 91–110.

Whalley, W. B., 1971, Observations of the drainage of an ice-dammed lake—Strupvatnet, Troms, Norway: Norsk Geografisk Tidsekritt, v. 25, part 3-4, p. 165–174.

Yesenov, U. Y., and Degovets, A. S., 1979, Catastrophic mudflow on the Bol'shaya Almatinka River in 1977: Soviet Hydrology, v. 18, p. 158–160.

Young, G. J., 1980, Monitoring glacier outburst floods: Nordic Hydrology, v. 11, p. 285–300.

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