HYDROLOGIC AND BIOLOGIC CONSEQUENCES OF AN AVALANCHE STRIKING AN ICE-COVERED LAKE

by

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INTRODUCTION

Avalanche activity in alpine watersheds can produce major hydrological effects (Luckman, 1977). Avalanches can fill lake basins (Peev, 1966), temporarily impound rivers, creating lakes (Rapp, 1960), or cause floods (Vuichard and Zimmermann, 1987). The sudden discharge of large volumes of water from glacial lakes as a result of ice avalanche activity has led to considerable awareness and abundant literature on this topic (see Vuichard and Zimmermann, 1987). However the hydrological effects of large avalanches on ice-covered lakes have rarely been documented (see Schytt, 1965; Luckman, 1975), and the biological consequences of such events have never been documented. The extreme weather conditions, remote locations and hazards associated with these avalanches make observations of this phenomenon difficult and unlikely.

Deposition of wet snow over a continuous 8-day period in February 1986, resulted in a large avalanche in the Emerald Lake watershed (ELW) of Sequoia National Park, located in the southern Sierra Nevada, California, USA. Impact forces from the avalanche on Emerald Lake were sufficient to cause dramatic changes in the outlet stream of the lake. The fortuitous presence of a field team of snow hydrologists before and after the event presented the unique opportunity to document pre- and post-avalanche conditions of the lake and its outflow. Furthermore, ongoing research into the ecology of brook trout (*Salvelinus fontinalis*) by Cooper et al. (1988) permit evaluation of the direct effect of the avalanche on the resident trout population.

In this paper we document the hydrological changes from an avalanche striking ice-covered Emerald Lake, and report the effect this event had on the embryonic and juvenile stages of the resident trout population.

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SITE DESCRIPTION

Emerald Lake is located on the upper Marble Fork of the Kaweah River drainage, in the southern Sierra Nevada of California, USA (36°35'49"N, 118°40'30"W). The basin is an alpine cirque 120 hectares in area, ranging in elevation from 2800 to 3416 m (Figure 1). Basin topography is characteristically steep and rugged, with a mean slope of 31°. Exposure distribution is generally towards the north, with a slight bias towards the west. Terrain typically consists of cliffs that are too steep to hold snow, alternating with benches that accumulate snow during storms. Avalanches frequently occur during and immediately after snow events in most areas of the watershed.

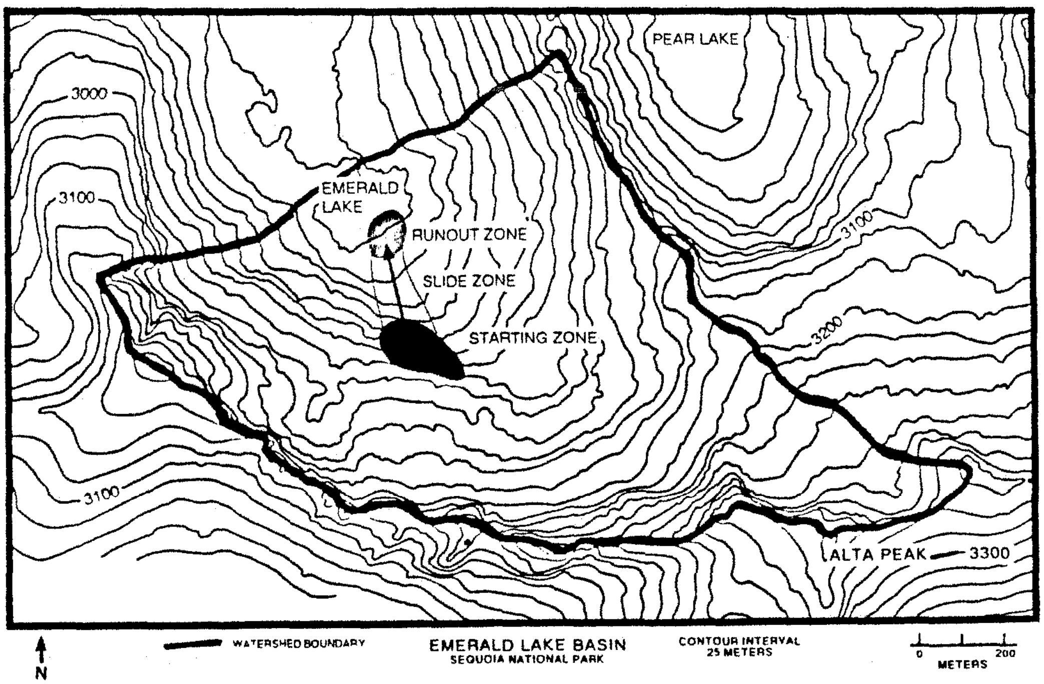


Figure 1. Topographic map of the Emerald Lake basin, with the avalanche area highlighted.

At the bottom of the drainage lies 2.85-ha Emerald Lake. The morphometry of the lake is characteristic of cirque catchments in the Sierra Nevada. The lake basin has a poorly developed littoral area, with granitic slabs that slope steeply towards maximum depth. Emerald Lake has a mean depth of 6 m, a maximum depth of 10.5 m, and a volume of 1.8×10^5 m^3. Lake sediments are organically rich and flocculent near the center, with conspicuous patches of sand and gravel in the southeast and northwest corners of the lake. On the west and southwest sides of the lake cliffs rise abruptly from the lake shore.

METHODS

Snow water equivalence (SWE) of a storm was calculated by multiplying the depth of new snow by its integrated density. One-meter square snowboards were used for event sampling. However the SWE of the storms from February 10-17 was determined by digging a snowpit to a stratum recognizable as the snow surface prior to the storm, as all snowboards were irretrievably buried by the snow deposition. Duplicate snow samples for density were collected along the wall of the snow board or pit with a clear, graduated, beveled, PVC tube 5-cm in diameter and 50-cm in length. The snow sample was transferred to a clean plastic bag and weighed with a spring scale. The weight of the sample divided by the tube volume gave sample density. Snow temperatures were determined with a digital thermometer (±0.2°C). Snow crystal type and size was determined visually by comparing falling snow crystals to a standard snow crystal index card.

Stage height of the Emerald Lake outflow was recorded automatically every 15 minutes on an Easylogger field computer, from voltage generated by a Montedero-Whitney pressure transducer installed 18 m downstream of the lake outlet [Dozier et al., 1987].

RESULTS and DISCUSSION

Hydrologic Effects

Massive snow deposition to the basin occurred during a series of snow storms, from February 10-17, 1986. Accumulation from this storm was 2.02 m at the lake, with an integrated snow density of 410 kg m^{-3}, and a snow water equivalence of 83 cm. Crystal types in the falling snow varied from heavily rimed stellars to graupel. Temperature of the new snow ranged from -3 to 0°C. Strong winds that accompanied the wet snowfall resulted in large accumulations of snow on steep cliffs that normally slough snow during storms. Avalanches occurred intermittently in the watershed throughout the storm. During a brief period of clear weather on the afternoon of February 17, large crown fractures were observed in most avalanche starting zones, with the notable exception of the cliffs to the southwest of the lake.

Snowfall and wind markedly increased in intensity at about 1600 hrs on February 17. At this time the field team retreated from the watershed for safety reasons. Upon returning to ELW on the morning of February 18, the researchers discovered that a large avalanche had run from the avalanche starting zone on the slopes southwest of the lake to a runout area on the southeast corner of the lake (Figure 1).

We used standard snowpack protocol and the equations for avalanche dynamics presented in Leaf and Martinelli [1977] to describe the avalanche and its movement. The snowpack in the starting zone consisted of a relatively high density, well-bonded slab overlying a relatively low density, poorly-sintered layer of the snowpack (Figure 2). The avalanche ran on a sliding surface of dry powder, deposited by a cold storm on February 6, with an average density of 55 kg m^{-3}, a depth of 9 cm, and a temperature of -9°C. The avalanche consisted solely of snow from the storm, assumed to have the same density as snow at the lake outlet (410 kg m^{-3}). The crown fracture averaged 2-2.5 m in height. The slope of the starting zone varied from 35° to 65°, with a mean slope near 40°. Wet snow, rapid sintering and strong winds apparently account for this atypical accumulation of snow on steep slopes. The starting zone was about 300 m above the runout zone. Avalanche debris on the lake covered 850 m^2, with a maximum height of 3.7 m. We estimate that the avalanche struck the lake with a velocity of 20 m sec^{-1}, and a force of 2.12×10^6 N.

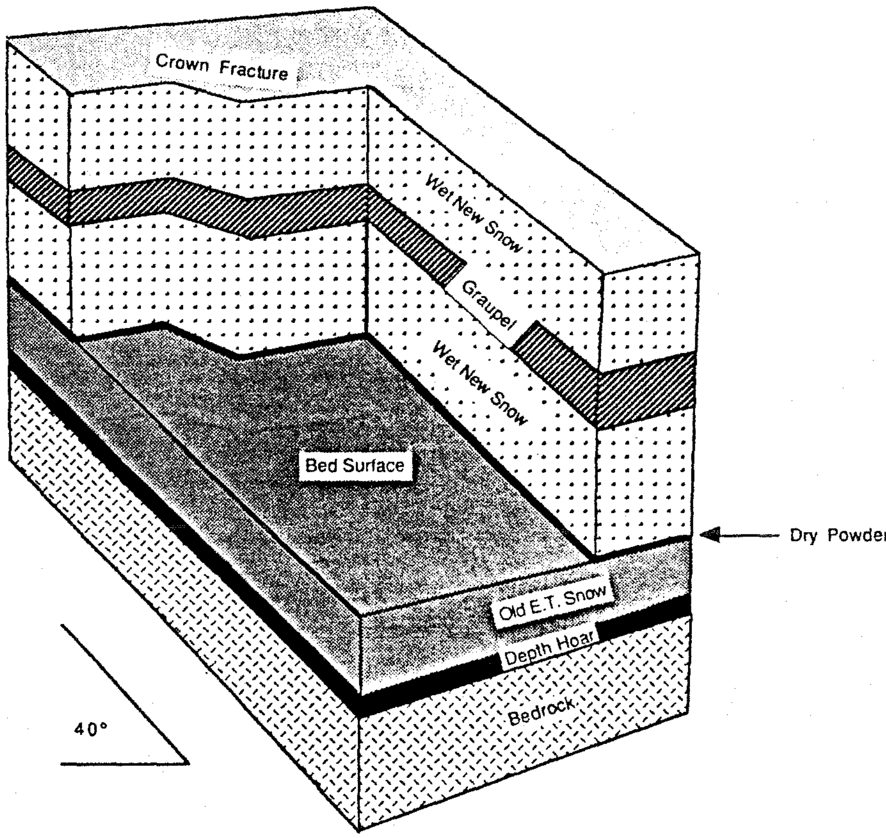
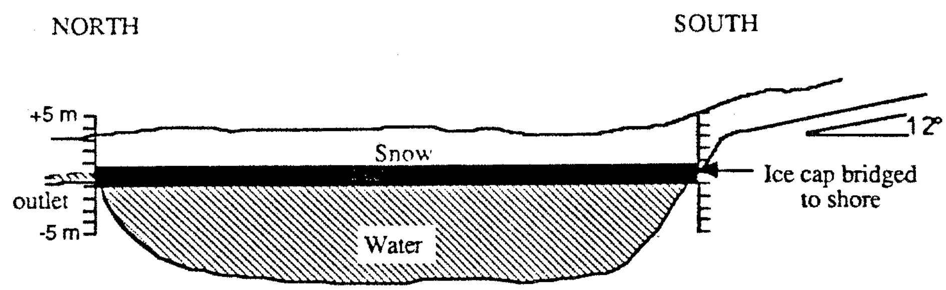


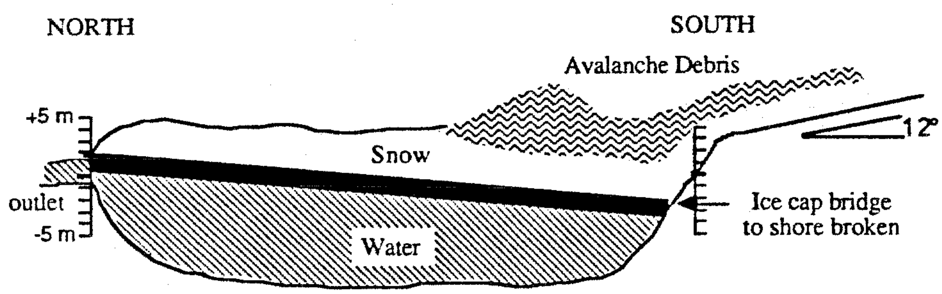
Figure 2. Stratigraphy of the snowpack at the starting zone of the avalanche.

We hypothesize that during and after the avalanche struck the ice-covered lake, the ice acted as a cohesive unit, analogous to a floating lid covering the lake surface (Figure 3). Lake ice was fractured continuously along the lake's perimeter. No ice fractures were observed on the lake surface, nor were ice blocks from the frozen lake surface deposited on shore. The avalanche may have acted as a plunger, pushing the ice below the hydrostatic level of the lake. This piston-type action then forced lakewater into the lake outlet, and up onto the opposite shore. Snowpits dug on the northeast shore of the lake were stained yellow from ground level to 50 cm above the ground, indicating that organic sediments from a wave of lakewater may have reached that height there. Lakebed sediments were observed 50-100 cm above the shoreline on the north and northeast sides of the lake, along with trout remains, after snowmelt in the summer of 1986. Snowpit data from the lake shore, and visual observations of lake ice, are consistent with the proposed hypothesis.

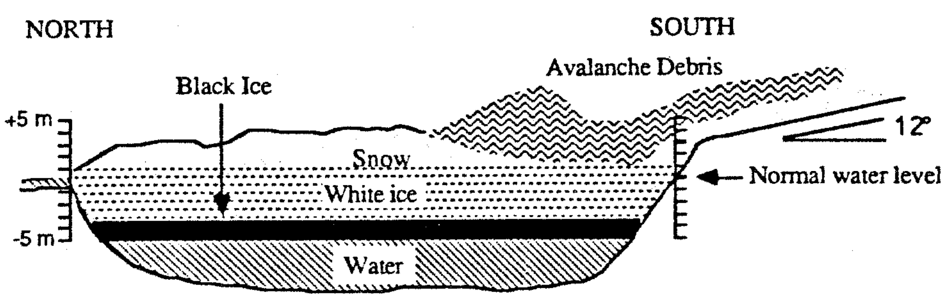
Ice thickness on the lake was measured at a site near the middle of the lake. Prior to the avalanche the ice was 1.7 m thick, displacing 43000 m^3 of the lake's 180000 m^3 of water. After the avalanche the ice thickness of the lake increased to 6 m, displacing another 90000 m^3 of water from the lake. The new ice was a combination of snowfall, lake slush,



a) Emerald Lake before avalanche. 21:00 hours, February 17, 1986.



b) Initial response to avalanche. ~21:20 hours, February 17, 1986.



c) Two hours after impact. 23:20 hours, February 17, 1986.

Figure 3. Response of ice-covered Emerald Lake to the avalanche event on February 17, 1986.

and avalanche debris. Seventy percent of the unfrozen water in the lake was removed from the lake basin by the impact of the avalanche, and forced into the outlet channel.

The resulting outflow discharge was the single largest hydrographic event in water years 1986 and 1987 (Figure 4).

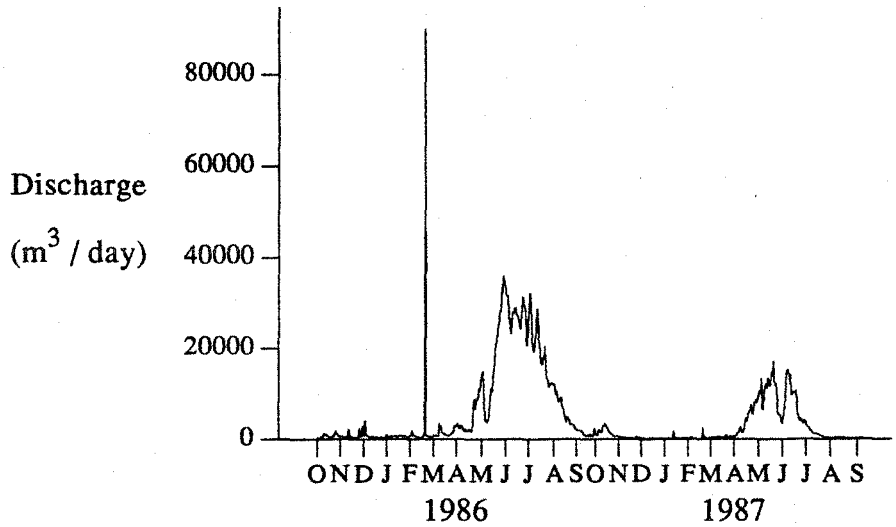


Figure 4. Daily discharge from Emerald Lake, water years 1986 and 1987. Discharge from the avalanche on Emerald Lake was several-fold greater than peak discharge during snowmelt runoff.

Stage height in the outflow stream increased from winter baseflow of 20 cm to an average of 86 cm in the 15 minute recording interval ending at 2135 hrs. At the next recording interval the stage height was 89 cm, the maximum value the transducer can register. Readings remained at 89 cm for 3 hrs, until 0050 hrs on February 18. Then, the recorded measurements began to decrease towards baseflow values, which were reached 23 hours later. Discharge reconstructed from the stage-height measurements was about 90000 m^3 over the 24 hr period, several-fold greater than peak discharge (in $m^{-3} day^{-1}$) at maximum snowmelt runoff (Figure 4).

Discharge from the lake cleared the outlet stream of snow to the inlet of the nearest pond, a distance of 94 m (Figure 5). Snow had covered the 4-m wide channel to an average depth of 3.5 m on the previous day. The volume of snow removed from the stream channel by the pulse of water produced by the avalanche on the lake was about 1300 m^3. Conservatively assuming this snow had the same density as the new snow, the mass of snow removed from the creek channel was 540000 kg. Continuous fractures were observed in the snow of the stream channel from the point where snow removal ceased (94 m downstream from lake outlet), to the confluence of the creek with the next downstream lake, as well as along the perimeter of that lake. This 700-m long fracture system was not present the previous evening.

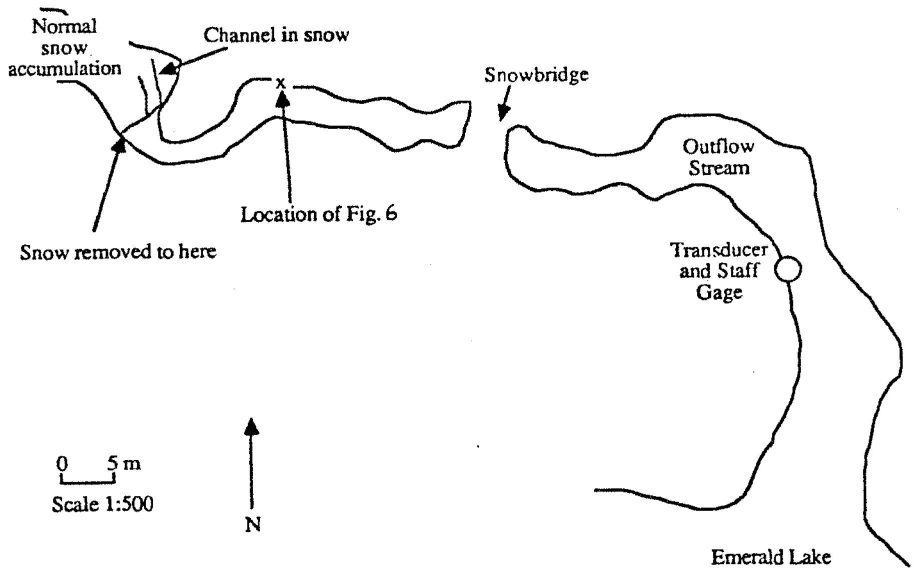


Figure 5. Longitudinal profile of the Emerald Lake outflow, detailing snow removal caused by a floodwave, created by the impact of the avalanche on the ice-covered lake.

Reconstruction of the hydrologic response in the outlet stream to the avalanche on Emerald Lake was performed using observations of snowbank stratigraphy in the channel. Snowbank stratigraphy at a location in the creek 72 m from the lake outlet is used as an example (Figure 6). We believe a floodwave was produced in the outflow stream that reached a maximum height of 1.6 m (Figure 6). The presence of sediments to 2 mm in diameter on the snowbank to the 1.6 m height are consistent with the higher velocities and turbulent flow of a floodwave. Channel capacity was sufficient to accept the large volume of water. Undercutting of the streambank, from 0.0 to 1.2 m above the streambed, suggests maximum velocities of the floodwave were attained at this stage height. Large rocks and snow formed a barrier in the channel 94 m downstream from the lake outlet. Ponding in the stream channel is indicated by the presence of organic materials at a height of 1.6 to 2.0 m. The smooth texture and even vertical face of the snowbank at this level further supports the supposition that ponding occurred. We hypothesize that snow in the stream channel above this height collapsed into the water column. The snowbank from 3.3 to 2.0 m above the baseflow water surface had the rough texture of normal snow, supporting our contention that water did not reach this height. When water rose to the 2-m stage height, the barrier was overtopped. A channel was eroded in the barrier. Stage height then slowly declined over the next 24 hours as the snowpack, avalanche debris, and ice on Emerald Lake came into hydrostatic equilibrium with lakewater.

Observations of the streambed in the outflow channel document many changes in channel morphometry. Drift logs to 3.5 m in length and 60 cm in diameter were moved as far as 30 m downstream. Scouring of the streambed was observed throughout the exposed

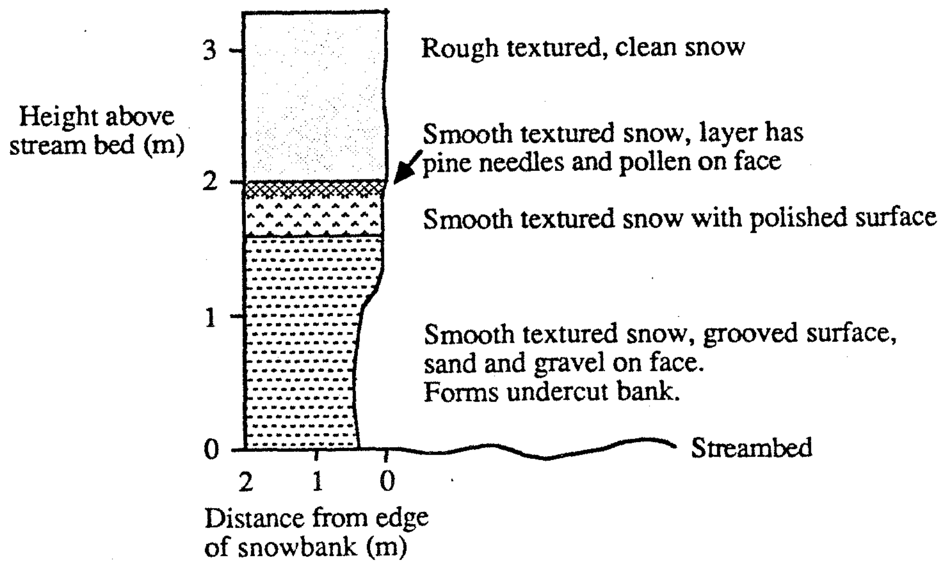


Figure 6. Streambank profile 72 m downstream from the Emerald Lake outflow. The face view presents deposition of sediments and organic matter on the snowbank. The side view illustrates the different erosion patterns on the snowbank caused by the floodwave.

stream channel. Sand and gravel were moved and redistributed throughout the channel, as were fines and organic sediments. The fracture lines in the 700-m of channel that extended to the confluence with the downstream lake indicate that the floodwave also disturbed this section of channel.

Biological Effects

During the 1985 spawning season for brook trout (Oct-Nov), the Emerald Lake outlet was searched every two to three days for nest sites (Cooper et al., 1988). To determine the survival rate of embryos and sac fry, biologists tagged each nest site. A subset of nine nests was placed in egg baskets. The egg baskets were 15 cm deep and buried *in situ* with their tops level with the streambed. As embryos hatched in the egg baskets they were transferred to *in situ* emergence traps. All egg baskets and emergence traps were moved by the floodwave of February 17. Two baskets were crushed, the remainder covered with silt or fine sand. Most nests were either covered by sand and fine sediments, or washed away. Embryos and sac fry had a survival rate of close to 90% before the flood (Figure 7). After the flood survival from hatching to emergence was only 2.5% (Cooper et al., 1988).

Floods are known to be a source of brook trout mortality (Power, 1980). Brook charr redds were devastated by winter floods severe enough to scour the substrate, in Sagehen Creek, California (Seegrist and Gard, 1972). The brook charr year classes of 1965 and 1966 were nearly eliminated in a series of catastrophic floods in Valley Creek, Minnisota (Elwood and Waters, 1969). Floods from Hurricane Agnes scoured Burns Run in Pennsylvania, causing a 96% mortality of young of the year brook charr (Hoopes, 1975).

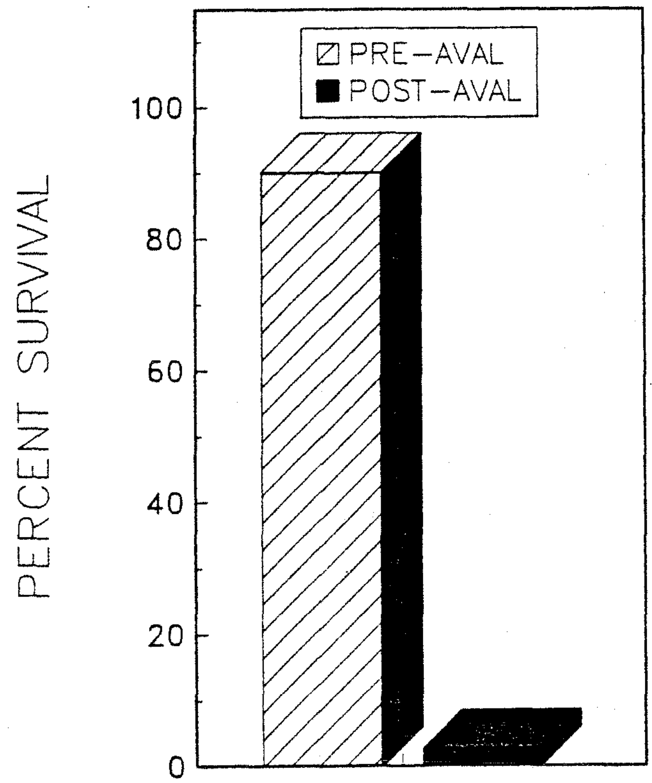


Figure 7. Percent survivorship of brook trout embryos and sac fry before the avalanche compared to percent survivorship after the avalanche, in the Emerald Lake outflow.

Scouring of the streambed in the Emerald Lake outlet by the floodwave may explain the decrease in survival of the outlet's embryo and sac fry population of brook trout. Egg basket mortality was likely caused by suffocation resulting from sediment deposition. Most of the nest mortality was probably due to scouring by the floodwave (Scott Cooper, personal communication). The finding of lake bottom sediments and trout remains on the shore of the lake suggests that similar scouring and trout mortality occurred in the lake. The finding of crushed egg baskets, placed in the spawning ground located on the western side of the lake at the base of another avalanche runout zone, corroborates this idea.

The two spawning areas in Emerald Lake are located in avalanche runout zones. A hypothesis that explains these observations, is that avalanches may establish and maintain trout spawning areas in some alpine lakes. Avalanche transport of sediments to these areas may establish spawning grounds for resident, or nearby, fish populations. Scouring from the impact of the avalanche may contribute to the maintenance of spawning grounds, by removing flocculent organic materials. Our observations suggest that avalanches on ice-covered lakes may be an important natural disturbance that contributes to the regulation of fish populations in Emerald Lake and its outflowing stream.

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