AQUATIC ECOLOGY AS A FUNCTION OF AVALANCHE RUNOUT INTO AN ALPINE LAKE

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ABSTRACT

Avalanche activity formed an avalanche plunge pool, developed a high-quality spawning area, and changed the water quality of Emerald Lake, a 2.72 ha tarn located at 2800 m in the southern Sierra Nevada of California. The submerged plunge pool at Emerald Lake is characterized by a distinct arcuate ridge surrounding a depression visible from the lake shore, at a depth of only 0.5 to 2.0 m. The plunge pool lies directly below the largest and most active avalanche path in the basin. The local topography has the distinct form identified by many researchers as unique to avalanche processes. Formation of the plunge pool by avalanches in Emerald Lake has resulted in the development of a high-quality spawning area for the resident brook trout (*Salvelinus fontinalis*) in this steep-walled section of the lake. The avalanche plunge pool covers only 2% of lake area but accounts for about 50% of the successful spawning in the lake. Snow accumulation in the lake from avalanche runout had a marked impact on the chemistry of lake water. The low values for alkalinity and pH at this site relative to other areas of the lake indicate that any increases in the acidity of snowfall will not be buffered and could have adverse effects on the local biota.

INTRODUCTION

Avalanche activity is common at high-elevation locations in the Sierra Nevada during the winter and spring seasons. The impact of avalanche activity on human life and on structures, railroads and highways has been documented for over a hundred years [cf. Tutton, 1931; Seligman, 1936; Armstrong, 1977]. However, much is still to be learned about the potential effects of avalanche activity on geomorphology,

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biology, and water chemistry of alpine sites. In particular, little is known on how avalanche activity may effect the aquatic ecology of high-elevation lakes.

The geomorphic effects of snow avalanches in mountainous regions have been recognized for many years. Reports on the geomorphic effects of snow avalanches first appeared in the scientific literature nearly three quarters of a century ago [Allix, 1924]. More recently, identification of avalanche impact landforms and the geomorphic processes causing them has received considerable attention in Scandinavia, Eastern Europe, New Zealand, and North America [Rapp, 1959; Peev, 1966; Caine, 1969; Luckman, 1977 and 1978; Tarquin, 1977; Gardner, 1983; Fitzharris and Owens, 1984; André, 1990]. Avalanche impact landforms may occur where the avalanche path intersects a slope of greatly reduced angle or where an abrupt change in flow direction is dictated by gross terrain features. These forms are typically an ellipsoid shaped depression caused by repeated removal of substrate in the center and redeposition around the margins. This process leads to a concave area surrounded by an arcuate or crescent-shaped distal ridge, much like the terminal moraine of a glacier, but a great deal smaller in scale. The forms have been referred to as avalanche scour pits [Davis, 1962] and avalanche pits [Serbenko, *in* Peev, 1966]. When filled with water, they are referred to as avalanche impact pits [Corner, 1980] and as avalanche tarns [Fitzharris and Owens, 1984]. When the depression is formed in a standing water body such as a lake or fjord they are called avalanche impact pools [Corner, 1980] or avalanche plunge pools [Liestøl, 1972].

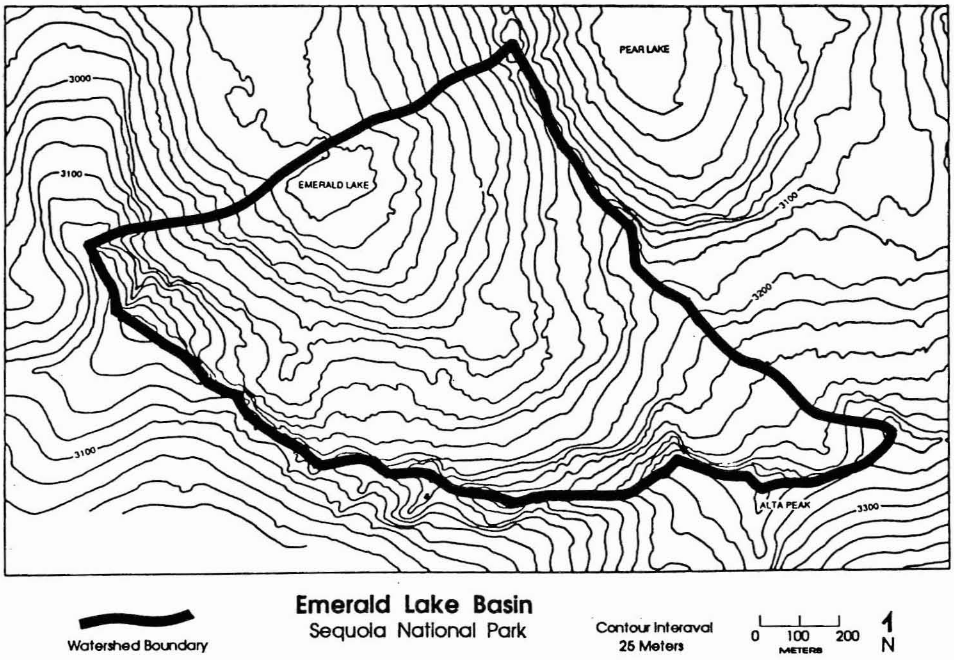

Figure 1. Topographic map of the Emerald Lake basin.

Avalanches that strike standing water bodies may affect the ecology of the lake in addition to forming plunge pools. The impact of the avalanche has the potential to cause mortality in developing embryos and fry. Alternatively, avalanche activity may increase the hatching success of the fish population by transporting gravel to hatching areas and by removing floculent organic matter from hatching areas. Additionally, the transport of snow by avalanches to the lake may change the chemical content of the lake water. In turn, this change in water chemistry make have a direct effect on the fish population.

Here we evaluate the potential effect of avalanche runout on the aquatic ecology of high elevation lakes in the Sierra Nevada. Our test site is Emerald Lake, located in Sequoia National Park in the southern Sierra Nevada. We make the case that Emerald Lake is representative of high-elevation lakes in the Sierra Nevada [Melack and Stoddard, 1991] and that knowledge gained at Emerald Lake can be applied to other lakes in the Sierra Nevada. We investigate the effects of avalanche impact and runout on the geomorphology of the lake, trout population, and water chemistry. We divide the avalanche activity into three areas: i) high-frequency/low-magnitude events, ii) medium-frequency/medium-magnitude events, and iii) low-frequency/high-magnitude events.

SITE DESCRIPTION AND METHODS

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 heavy snowfall events in most areas of the watershed [Williams and Clow, 1990].

Emerald Lake is a 2.72 ha cirque lake at the bottom of the basin, fed by two main inflows and six intermittent streams, and drained by a single outflow. The morphometry of the lake is characteristic of cirque catchments in the Sierra Nevada (Figure 2). 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 floculent 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.

Avalanche activity in the Emerald Lake basin was investigated on an *ad hoc* basis by snow hydrologists as avalanches occurred. An analysis of a large avalanche in February 1986 has been reported in Williams and Clow [1990] and Elder et al. [1990]. Geomorphic effects of avalanche activity were investigated by visual inspection and by divers in Emerald Lake. Egg deposition, embryo development, and embryo survival of brook trout were investigated in two ways. The first method was to count nesting sites and individuals by walking the perimeter of the lake and by snorkeling every few days. The second method was to dig up a subset of existing nests, place these nests in egg baskets, rebury the nests in the same location, and then census the survival rates in the egg baskets. Substrate type in nesting areas was investigated by divers. Chemical samples of lake water and snow were collected and analyzed using standard protocols reported in Williams and Melack [1991].

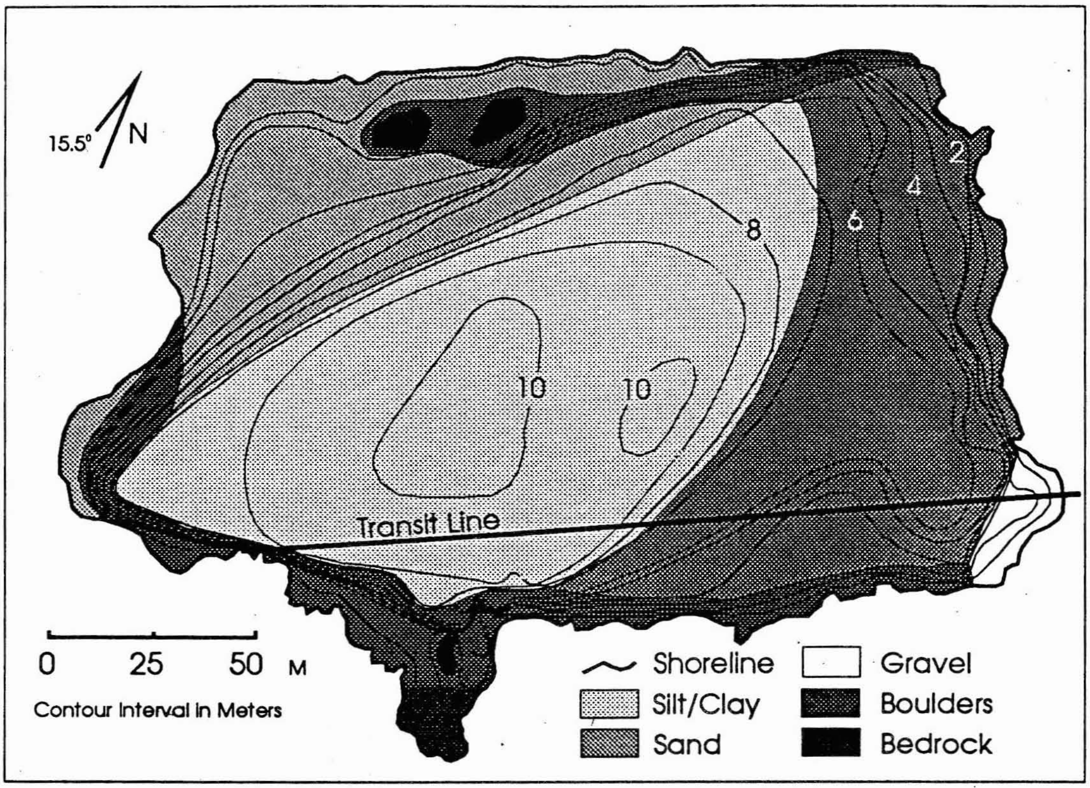

Figure 2. Bathymetric map of Emerald Lake. Transit line is detailed in Figure 3.

RESULTS AND DISCUSSION

High-Frequency/Low-Magnitude Events

Field observations show that avalanche events that are high in frequency and low in magnitude are small in all respects: low velocity, low impact pressure, small volume of material and short runout distance. The field observations are consistent with previous reports [e.g., Perla and Martinelli, 1978; Elder and Armstrong, 1987; Elder et al., 1991]. These avalanches are typically of two types: i) direct action sluffs and avalanches occurring during storms or ii) small sluffs releasing during warm-up. These small events are not effective in entraining material from the substrate because they usually travel over the snow surface and are not in contact with the substrate. By definition, they are not climax events. The avalanches do not reach the lake surface and do not have any direct effect on the lake. However, these high-frequency/low-magnitude events may be important in transporting material accumulating on the snow surface via rockfall from cliffs. In general, we can disregard the influence of high-frequency/low-magnitude events on the aquatic ecology of Emerald Lake.

Medium-Frequency/Medium-Magnitude Events

Medium-frequency/medium-magnitude events may be partially responsible for the creation and maintenance of the plunge pool and high-quality habitat for trout reproduction. The plunge pool at Emerald Lake is located on the western corner of the lake in an area where the lake bottom rapidly reaches a depth of more than 6 m (Figure 2). The plunge pool lies directly below the largest and most active avalanche path in the basin (Figure 1 and 3). The pool is well submerged, but does form a distinct arcuate ridge surrounding a depression visible from the lake shore. The impact pool has an area of about 1800 m^2, a maximum depth of about 6.5 m, and the depth of the distal ridge varies between 4 and 6 m.

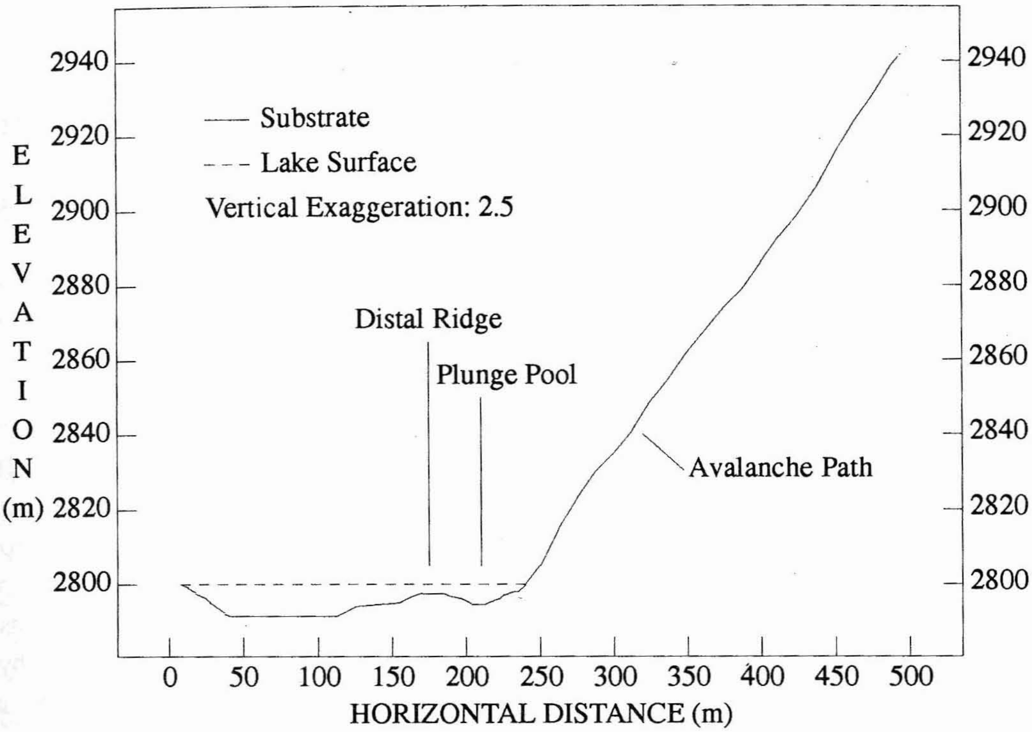

Figure 3. Cross-section of the avalanche plunge pool and avalanche path on the northwest corner of the lake. Transect location is marked on Figure 2.

The avalanche path above the pool has a mean slope of 42° and a length of 515 m, with a vertical drop of 350 m. The path has a steep bedrock gully at the top and the lower 75% of the path is made up of mixed talus ranging from about 1 m in diameter down to sands. The source of the talus is several highly-fractured, granitic cliff bands of up to 100 m in height. Rockfall onto the snow surface is commonly observed during the spring when the diurnal freeze-thaw cycles are most pronounced. Wet snow avalanches have been observed in the spring and are common after spring snow storms [Elder et al., 1991]. The talus slope has the distinct basal concavity at the toe of the slope attributable to debris transport by avalanches [Caine, 1969; Luckman, 1978]. Avalanches are the only geomorphic agent present that could produce this landform. The avalanche path and resulting impact pool are consistent with published examples in both form and observed processes, leaving little doubt that the existing pool was created and is maintained by avalanche activity. Medium magnitude avalanches appear to entrain debris from the substrate and carry debris fallen from surrounding cliffs.

Formation of the plunge pool by avalanches in Emerald Lake has resulted in the development of a high-quality spawning area for the resident brook trout (*Salvelinus fontinalis*) in this steep-walled section of the lake. Our snorkeling results suggest that there is intense competition among trout for nesting sites within Emerald Lake. We observed that embryos within a nest at Emerald Lake were often exposed by subsequent spawners reworking the same gravel and that the exposed eggs were often cannabalized by peripheral fish. This intense competition for nesting sites at Emerald Lake is typical for high-elevation areas of the Sierra Nevada, where spawning areas for trout are limited by the steep gradients typical of this area [Kondolf et al., 1987].

Transport of debris by avalanche activity to the northwest corner of the lake has raised the elevation of the lake bottom and created a littoral area that is exploited by the trout for nesting habitat. Spawning habitat in Emerald Lake is limited to an area near the lake's inflowing streams (about 15% of lake area) and the avalanche plunge pool (about 2%). Monthly young-of-the-year (YOY) counts in Emerald Lake conducted by divers show that in 1986 and 1987 55% of the YOY were from the plunge pool site and 45% from the inlet site, while in 1988 42% of the YOY were from the plunge pool and 58% from the inlet site. The avalanche plunge pool covers only 2% of lake area but accounts for about 50% of the successful spawning in the lake.

The high proportion of successful hatching at the avalanche plunge pool appears to be due to the high quality of the nesting area. Successful hatching of trout is dependent on substrate conditions. Trout lay their eggs in a pit (redd) excavated among bottom gravels. Females generally select habitats that have enhanced gravel permeability and intergravel flow to oxygenate eggs and allow fry to emerge through the bed surface. Winnowing of fine sediments by the female during construction of the redd further enhances oxygen transport to the eggs. Fine sediments (<4.75 mm in diameter) deposited in hatching areas render redds less permeable, impede fry emergence, and may cause high mortality and poor fry quality by reducing oxygen levels [Burns, 1970]. Inspection of the spawning areas by divers has shown that the inlet site consists primarily of sand and that the plunge pool site consists primarily of gravel. Sufficient disturbance may be created by the impact of the avalanche to remove floculent organic materials and maintain the gravel bars preferable for fish reproduction sites at the plunge pool.

The geomorphic and biologic effects of these medium sized avalanches appear to be confined to the lake itself. The forces of disturbances do not appear large enough to directly affect either the biology or geomorphology of the outlet stream. Visual observations suggest that these medium magnitude avalanches may run as often as several times a year. We have not recorded any increase in discharge at the outlet stream associated with these avalanche events.

Low-Frequency/High-Magnitude Events

A large magnitude avalanche with a return frequency of about 150 years struck Emerald Lake in 1986. 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 (SWE) of 83 cm. Mean accumulation for the basin was greater than 1.0 m SWE [Elder et al., 1991]. 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 sluff during storms [Williams and Clow, 1990]. The excessive snow deposition over a relatively short period, coupled with high winds, caused an avalanche cycle at the Emerald Lake basin that also covered much of western North

America. Many observations taken shortly after the cycle indicated that it was an uncommon and catastrophic period [Wilson, 1986]. Large amounts of mature timber were destroyed throughout the Sierra Nevada with trees up to 1.0 m dbh broken and uprooted and thousands of acres of forest decimated. Dendrochronological analysis showed that a large percentage of the trees were 125 to 150 years of age. Long runout distances were observed and low alpha angles resulted even where runout was retarded by mature stands of timber. The lowest alpha angle observed in the Sierra was 13°. Alpha angles of less than 18° are unusual in this region [Wilson, 1986]. Estimated impact pressures on Emerald Lake from the avalanche were sufficient to force 90,000 m^3 from the lake, about 70% of the lake volume [Williams and Clow, 1990; Elder et al., 1990]. The resulting floodwave in the outlet stream caused many changes in channel morphometry.

The low-frequency/high-magnitude avalanche cycle caused high mortality in the 1986 age class of brook trout. Nests site within the lake and in the lake outlet were tagged in the fall of 1985. A subset of nests were placed in egg baskets and reburied *in situ*, three at the avalanche plunge pool and nine in the outlet stream. All three egg baskets at the avalanche plunge pool were crushed from avalanche impact. All egg baskets in the outlet stream were moved downstream by the floodwave, but most were recovered. Two of the baskets were crushed and the remainder filled with silt or fine sand. Survival of embryos and sac fry decreased from close to 90% in February to 2.5% after the flood. Maximum counts of YOY from 1985 through 1988 show that 1986 had the lowest number of YOY. Maximum YOY counts were >600 in 1985, <200 in 1986, ~500 in 1987, and about 800 in 1988. The avalanche cycle in 1986 is at least partially responsible for the low survivorship of YOY in 1986. Missing age classes of trout are common in the Sierra Nevada [Erman et al., 1988]. Low-frequency/high-magnitude avalanches may be one factor responsible for missing age classes of trout in the high Sierra Nevada.

Mortality of brook trout in the outlet stream appears to have been compounded by the presence of snow banks. The transport rate of bed particles in a stream is a function of shear stress (τ) acting on the streambed. The shear stress under steady, uniform conditions is

$$\tau = \gamma D S \tag{1}$$

where γ is the fluid's specific weight, D in the mean fluid depth, and S is the slope of the fluid surface. From Eqn. 1 we can see that increased shear stress depends only on increased depth, not discharge, if specific density and slope are held constant. An increase in shear stress causes an increase in bedload transport. Erman et al. [1988] have shown that the presence of snow banks during rain-on-snow events in Northern California significantly raised the water level of flooding streams. The additional stage height provided by snow banks greatly increases the shear stress, thus increasing bedload transport. Increased particle movement may kill fish embryos and sac fry by crushing or burying them.

The resultant flood in the outlet stream channel at Emerald Lake had similar attributes to the rain-on-snow flood event described by Erman et al. [1988]. The mean channel width in the affected section is about 4 to 5 m. Although the channel is restricted for about 20 m distance on one side by bedrock, most of the affected reach has low banks of about 0.4 to 0.6 m spilling onto a floodplain. During the flood event the mean channel width did not change and remained confined to the normal bankfull discharge width. However, the channel depth was greatly increased during the flood because the dense snowpack resisted bank erosion and effectively raised the bank height to the depth of the snowpack. Prior to the flood the channel was covered with snow to a depth exceeding 3 m. The flood excavated the channel a distance of 94 m downstream from the outlet, leaving banks greater than 3 m deep along the natural channel boundaries. Examination of the snow banks after the flood indicated that flow depths had reached at least 2.0 m for some indeterminate period [Williams and Clow, 1990]. Assuming that the bankfull discharge has a mean stage somewhere below 1.0 m depth, it is safe to say that the presence of snow banks caused the bed shear stress to double during this flood (see Eq. 1). A small increase in critical shear stress results in a large increase in material transport rate [Erman et al., 1988] and can explain the crushing and silting of egg baskets in the outlet stream.

Snow accumulation in the lake from the large avalanches in 1986 had a marked impact on the chemistry of lake water. During the period of melting lake ice, subsurface water chemistry under the avalanche runout zone differed markedly from the other three sampling sites in the lake, as illustrated in this example from June 10, 1986 (ANC is acid neutralizing capacity, C_b is sum of base cations):

Table 1. Chemical content of plunge pool and lakewater.

	ANC (μeq L^{-1})	pH	C_b (μeq L^{-1})	SiO_2 (μmol L^{-1})
Avalanche plunge pool	0	5.5	9	3
Average of other sites	24	5.7	24	21
Snowpack	0	5.4	3.1	0

These solute values in subsurface lakewater from the plunge pool are very similar to those of bulk snowpack chemistry at the same time [Williams and Melack, 1991], indicating that the source of lakewater at this location was melt from the accumulation of avalanche debris in the lake. The ANC value of 0 μeq L^{-1} shows that the lakewater had no ability to buffer acidity at this site. Experiments have shown that mortality of trout fry occurs when pH levels are ≤ 5.5 for a period equal to that of snowmelt runoff [Gunn and Keller, 1985]. Furthermore, Barmuta et al. [1990] have shown through experimental manipulations that when lakewater pH is ≤ 5.5, there is major restructuring of the zooplankton population and possible cascading effects on trout populations. The pH value of 5.5 at the avalanche plunge pool is at this threshold level were deleterious effects begin to occur in the biological community. However it should be notes that the water quality of interstitial waters may differ from that of the overlying lake water.

Mortality of embryos and sac fry in 1986 may have been compounded by the low pH of snow transported by avalanches to lakes and streams. Low numbers of YOY were recorded in all lakes of the Marble Fork watershed in 1986 by regional fish surveys conducted from 1985 through 1988. It would appear that some factor operated over the entire Marble fork basin in 1986 that resulted in low recruitment of YOY.

Mortality of brook trout caused by crushing from avalanche impact or flooding effects is unlikely to have occurred throughout the entire basin. However, the low alpha angles from the avalanche cycle of 1986 suggest that many runout zones may have included lakes and streams. Compounding the addition of snow transported to lakes by avalanches was the large amount of snowfall in 1986 that fell directly on lakes as well as in their catchments. The low pH values of snow and avalanche deposition in 1986 may have been a contributing factor to the high mortality of YOY brook trout in 1986 throughout the Marble Fork basin.

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