SNOWMELT CONTRIBUTIONS TO FLOODING IN THE LAKE TAHOE BASIN

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ABSTRACT

Lake Tahoe receives national attention for its declining water quality and the massive public investments in attempts to halt and reverse that decline. Much of the nutrient and pollutant load is delivered to the lake during large runoff events. This paper attempts to contribute to the understanding of those larger events by describing the flood history from the record of gaged tributaries to the lake and the mechanisms of large-flow generation in the Lake Tahoe basin. Although snowmelt runoff every spring produces significant flows of long duration, the mid-winter rain-on-snow events cause the highest peaks. Because the lower extent of the tributary catchments is the lake at an elevation of about 1900 m, only the warmest storms produce substantial rainfall in the basin. Nevertheless, some of these storms have generated massive amounts of runoff and sediment. In most cases, the snow cover influenced the release of water to streams without adding much volume from melt. However, there were a few notable exceptions with significant snowmelt.

INTRODUCTION

Lake Tahoe is widely recognized as one of the most beautiful mountain lakes in the world. However, its attractiveness has led to its degradation through the impacts of visitors and development. The clarity of the lake has decreased steadily over the past several decades as the biological productivity of the lake has increased in response to increased nutrient loading (Goldman, 1974). Much of the anthropogenic nutrient input is believed to be associated with accelerated sediment yield from roads, residences, commercial zones, and other disturbed areas (e.g., Strong, 1984; Elliott-Fisk, et al., 1996). Since the 1970s, various agencies of California, Nevada, and the federal government have sought to minimize impacts of human development in the basin and reduce sediment and nutrient yield into the lake. Billions of dollars have been and will be invested in land acquisition, waste export, and erosion control programs. Innovative, state-of-the-art practices in watershed restoration are being developed at Lake Tahoe. Nevertheless, there is substantial lag in geomorphic and ecological processes that affect sediment and nutrient transport and, ultimately, lake clarity. Therefore, several decades may elapse before there is any detectable response to the current efforts at halting the degradation of Lake Tahoe.

The physical setting of Lake Tahoe is distinctive because the lake occupies such a large fraction (more than one-third) of its basin. This feature allowed the concept of a drainage basin or watershed directly affecting the lake to be easily visualized and understood by the public, politicians, and agency decision-makers. The basin area draining to the outlet of the lake at Tahoe City is about 1310 km^2 (506 mi^2), which includes about 500 km^2 (192 mi^2) of lake surface. Lake Tahoe has an average surface elevation of 1898 m (6225 ft). The lake level has been controlled by a dam at its natural outlet since 1874. The current dam provides about 2 m (6 ft) of regulation and a capacity of 920 million m^3 (745,000 acre-feet). Above the lake, slopes rise steeply to the Sierra Nevada crest on the west side of the basin and the Carson Range on the east side. Elevations along the drainage divide range from about 2250 m (7400 ft) to 3320 m (10880 ft). Most of the basin is forested with a variety of upper-elevation conifers. The thin, poorly-developed soils of the basin tend to be highly erodible.

The climate of the Lake Tahoe basin reflects the Mediterranean-type climate of California, the elevation of the basin, and its location east of the Sierra Nevada crest. Average annual precipitation ranges from about 500 mm (20 in) over the lake surface to more than 2000 mm (80 in) in areas near the western divide (Lind and Goodridge, 1978). The west shore of the lake receives roughly twice the precipitation of the east shore. About half of the annual precipitation falls between January and March with another third from October through December. Average snowpack water equivalence on April 1 ranges from 30 cm at snow courses at lower elevation and on the east shore to more than 150 cm at some snow courses high on the west shore. This note briefly describes some aspects of the role of snow in generating floods in the Lake Tahoe basin.

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Presented at the Western Snow Conference 1999, South Lake Tahoe, California

FLOOD HISTORY

Although maps of monitoring stations suggest a relatively dense network of stream gages in the Lake Tahoe basin, most of these gages have been operated for short periods or intermittently. Unfortunately, the record available for flood analysis is quite limited. Only two tributaries to Lake Tahoe have been gaged continuously for more than 35 years: Blackwood Creek (#10336660), 1961 to present, and Trout Creek near Tahoe Valley (#10336780), 1961 to present. Three other stations have relatively long records: Third Creek near Incline Village (#10336698), 1970 to present, Ward Creek (#10336676), 1973 to present, and Upper Truckee River near Meyers (#10336600), 1961 to 1986. There are 40 other stations with short records available from the U.S. Geological Survey within the Lake Tahoe basin.

Records of peak flows from the five gaging stations mentioned above were examined in an attempt to identify characteristics of the main floods in the basin during the past four decades. Again, the short period of overlap in the records from different gages limited the comparisons between sites. The very largest events were common between the various sites: January 1997, February 1963, December 1964, March 1986, February 1986, January 1980, February 1982, and January 1970. Each of these events was characterized by large amounts of rainfall and very warm temperatures. The response of the five streams to lower-magnitude storms varied considerably. For example, table 1 compares the ranks of floods between the stations with the longest coincident period of record. Beyond the largest three or four events, floods in Blackwood Creek and Trout Creek had very different rankings. Rain-on-snow events produced the 18 highest flows in Blackwood Creek, but spring snowmelt peaks ranked as high as 6 and 8 in Trout Creek. Midwinter rain events did not produce extraordinary flows in Third Creek near Incline Village. More than 70 percent of its drainage area is above 2440 m (8000 ft) (Glancy, 1988). Therefore, except in the warmest storms, only a small proportion of the catchment receives rainfall and contributes snowmelt. Spring snowmelt tends to produce the highest flows in Third Creek.

Table 1. Rank of principal floods in two tributaries to Lake Tahoe during 1961 to 1998.

Date	Blackwood Creek	Trout Creek
2-1-63	3	1
12-24-64	2	4
3-16-67	6	15
12-21-69	8	73
1-16-70	9	20
1-21-70	4	16
1-13-80	11	7
12-20-81	5	17
2-16-82	10	10
6-18-83	19	6
2-18-86	11	5
3-8-86	7	3
6-26-95	32	8
5-16-96	14	9
1-2-97	1	1

Two stations on the Truckee River downstream of Lake Tahoe have been operated for almost a century. A gage just below the lake at Tahoe City (#10337500) is located at an elevation of 1895 m (6217 ft) and controls a drainage area of 1310 km^2 (507 mi^2). The second gage (#10346000) is located at Farad at an elevation of 1570 m (5153 ft) and measures discharge from a drainage area of 2414 km^2 (932 mi^2). Streamflow at both stations is strongly influenced by changes in storage in Lake Tahoe (and other reservoirs for the Farad gage), which limits the usefulness of the data from these gages in studies of flood generation. Only two events were found in the list of the ten highest peaks at each station: January 2, 1997 (peak of record at Tahoe City and #4 at Farad) and March 8/13, 1986 (ranked third at Tahoe City and ninth at Farad). The other floods in the list of the ten highest peaks at the Truckee River at Farad station were November 1950 (rank 1), December 1937 (rank 2), March 1907 (rank 3), December 1955 (rank 5), December 1964 (rank 6), March 1928 (rank 7), February 1963 (rank 8), and January 1980 (rank 10). All these events, except that in March 1928, were among the largest recorded floods on other major rivers of the Sierra Nevada. Although intense rainfall contributed most of the water to these floods, each had a significant snowmelt component (Kattelmann, et al, 1991).

THE ROLE OF SNOW COVER IN GENERATING FLOODS AT LAKE TAHOE

Because of the topographic and climatic characteristics of the Lake Tahoe basin, snow is a critical aspect of the hydrology of the catchments tributary to the lake. A seasonal snowpack begins to develop in November of most years. Although a persistent snow cover is usually present over most of the land area of the basin from late November through May, portions of the basin below about 2000 m (6560 ft) may have thin or intermittent snow cover in some years. Snow affects runoff generation in the Lake Tahoe basin in three principal ways. It is available for melt in the spring when the snowpack energy balance becomes positive. It is available for melt during warm midwinter storms. Lastly, it can delay the release of water from the base of the snowpack.

Spring snowmelt dominates the annual hydrograph of most Sierra Nevada rivers by generating sustained high flows for a two to three month period (e.g., Kattelmann, 1991). Catchments in the Lake Tahoe basin behave similarly in that regard to their counterparts elsewhere in the range. The snowmelt hydrograph is largest in those catchments with a large fraction of their area at higher elevations. More than 200 mm of runoff is generated during the peak month of snowmelt. In the extraordinary years, such as 1983, more than 800 mm of runoff was produced in one month in some catchments. Nevertheless, the instantaneous peaks are not particularly high. In various tributaries to the lake, specific peak discharges during snowmelt runoff ranged from 0.1 to 0.3 $m^3 s^{-1} km^{-2}$ (8 to 30 $ft^3 s^{-1} mi^{-2}$). The snowmelt hydrographs of the small (1 to 140 km^2 [0.4 to 54 mi^2]) catchments of the Tahoe basin show a strong diel pattern because there is little storage or lag in the channels.

As in other parts of the Sierra Nevada (Kattelmann, 1997), the largest floods in most tributaries to Lake Tahoe have occurred when warm storms bring intense rain to higher elevations. The primary influence of these warm storms is simply the increase in contributing area with rainfall-runoff production from higher-elevation areas that otherwise receive snow during most winter storms. Rainfall amounts can become substantial during some of these storms. For example, up to 180 mm of rainfall has been recorded in 24 hours at the Central Sierra Snow Lab near Soda Springs at 2100 m, a few kilometers northwest of the Lake Tahoe basin (Azuma and Berg, 1990). During the January 1980 storm, 167 mm of rainfall was measured in 24 hours and 278 mm rainfall was measured in 48 hours at the Ward Creek No. 3 SNOTEL site in the Lake Tahoe basin (Moreland, 1981). There is also the potential for some melt to occur from convective heat exchange and condensation when temperatures are high and winds are strong. However, because the lowest elevation of the catchments at Lake Tahoe is lake level at 1898 m (6225 ft), air temperatures never approach the 10°C or even 15°C that can occur in the foothills of the Sierra Nevada during the warmest storms. Most of the snow cover in the Lake Tahoe basin is rarely exposed to sufficient energy during rain-on-snow events to generate significant melt. The portions of the Lake Tahoe basin between lake level and about 2300 m (7500 ft) receive the most energy during warm storms and can produce up to 25 mm (1 in) of melt per day (assuming an average temperature of 5°C). Thin snow cover near lake level can limit the amount of snow available for melt.

The ability of snow cover to regulate the release of water to streams may be much less than commonly assumed. Some recent results from the Central Sierra Snow Laboratory (Kattelmann, 1997 and in review) suggest that snowpacks stored less than 2 percent by volume of the incident rainfall. For the data set of 42 rain-on-snow events with adequate records of rainfall and outflow timing, lag times between the onset of rainfall and the onset of snowpack outflow averaged about 4 hours when the snow was less than 1 m deep and about 6 hours when depth exceeded 2 m.

Two unusually warm storms affected the Lake Tahoe basin in the past few years. The storm of May 15-16, 1996 occurred during the early part of the spring snowmelt season. Warm storms are quite rare during spring in the Sierra Nevada, but this event was a notable exception. Heavy cloud cover preceding the storm reduced radiation-induced snowmelt, but also reduced nighttime heat loss from the snowpack. Rainfall was observed above 3600 m in the southern Sierra Nevada, and air temperatures exceeded 10°C in the Lake Tahoe basin. This event produced the ninth highest flow on record in Trout Creek and the fifth highest peak on record in Third Creek. The flood of record in many streams of the Lake Tahoe basin occurred at the beginning of 1997. Intense rainfall and very warm temperatures produced excessive runoff throughout the Lake Tahoe basin. Rainfall for the storm period exceeded 450 mm at the Central Sierra Snow Lab, and air temperatures averaged about 5°C at this site at 2100 m (6900 m). Flood peaks were up to 50 percent higher than the previous flood of record in some tributaries to Lake Tahoe.

IMPLICATIONS FOR SEDIMENT TRANSPORT

The various flood processes in the tributaries to Lake Tahoe influence sediment delivery to the lake in different ways. Instantaneous concentrations of suspended sediment and nutrients have been found to be highest during summer thunderstorms and rain-on-snow events (Glancy, 1988). However, the total loads of sediment and nutrients transported to the lake are much higher during spring snowmelt runoff because of the sustained high flows (Glancy, 1988). The short-term intense floods have another critical influence on sediment delivery by destabilizing the channel system. Because erosion of streambeds and banks account for the vast majority of sediment delivered to the lake (Nolan and Hill, 1987), high-magnitude floods that alter channel geometry can provide a sediment source for subsequent smaller events. When streams are out of equilibrium following major floods, sediment yields remain high for years (Glancy, 1988). Recovery of Blackwood Creek from the 1964 flood was believed to take decades (Nolan and Hill, 1987). The 1997 flood has reset the stage again.

ACKNOWLEDGMENTS

An evaluation of the physical hydrology of the Sierra Nevada supported by the NASA Earth Observing System program through a grant to Jeff Dozier at the University of California, Santa Barbara contributed to this paper.

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