SNOW HYDROLOGY OF AN ALPINE BASIN IN THE SIERRA NEVADA

by

Richard Kattelmann[1]

INTRODUCTION

The importance of the snow zone as the principal water source for much of California is well-known. Extensive networks of storage and diversion structures and hydroelectric generation facilities have been built to take advantage of seasonal snowmelt runoff in Sierra Nevada rivers. An operational capability for forecasting streamflow has also been developed to optimize the use and distribution of water resources of the Sierra Nevada. This capability is largely based on the work of the Co-operative Snow Investigations at the Central Sierra Snow Laboratory and a variety of other studies in the forest belt. The highest parts of the Sierra Nevada snow zone have received much less attention despite their extensive area, vast snow resources, and critical contribution to summer streamflow. The snow cover of the alpine zone is monitored with more than 100 snow courses and snow sensors for operational forecasting, but research on basic hydrological processes in this zone has been limited (Kattelmann and Berg, 1987).

The first detailed study of the hydrology of an alpine basin in the Sierra Nevada was recently completed in Sequoia National Park. The project was undertaken in support of an evaluation of the sensitivity of alpine ecosystems to changes in precipitation chemistry. A major goal of this study was to identify and quantify the hydrologic processes and fluxes throughout the representative basin of Emerald Lake. Measurement and estimation of the various water fluxes through the basin were useful to studies of the aquatic chemistry and biology, soils, and terrestrial vegetation of the basin as well as in modeling efforts and assessment of the susceptibility of this ecosystem to changing chemistry of precipitation. Results of this study have been described in a series of reports and papers (e.g., Dozier, et al., 1989; Tonnessen, in review). This paper outlines the descriptive snow hydrology of this small part of the Sierra Nevada alpine zone.

STUDY AREA AND MEASUREMENT PROGRAM

The Emerald Lake basin is located in the Kaweah River drainage on the western slope of the Sierra Nevada (Figure 1). It is approximately 5 km ESE of Lodgepole in Sequoia National Park. The area of the basin is approximately 120 hectares, of which the lake covers about 3 hectares. Elevations range from 2800 m at the outlet of Emerald Lake to 3415 m at Alta Peak, and both subalpine and alpine vegetation is present. The average gradient of the basin is 30 percent, although some slopes in the basin are considerably steeper (Figure 2). The Emerald Lake basin is generally north-facing, and its outlet stream flows north to the Marble Fork of the Kaweah River.

The Emerald Lake basin is a granitic cirque carved by Pleistocene glaciation (Matthes, 1965). More than one-third of the basin area is exposed bedrock, and almost all of the remainder is solid rock covered by a thin mantle of talus, colluvium, or poorly developed soils (Huntington and Akeson, 1986). In general, the bedrock of the basin floor and cliffs was only recently exposed by glacial erosion and frost-action. The relatively unweathered nature of the rock has important implications with respect to the hydrology and hydrochemistry of the basin: groundwater storage, water residence time, and chemical buffering capabilities are all low compared to forested basins with deep soils (Moore and Wahrhaftig, 1984).

Streamflow leaving the basin has been measured since October 1983 by the U.S. Geological Survey in cooperation with the National Park Service. Studies sponsored by the California Air Resources Board began in autumn of 1984. Most hydrologic and micro-meteorologic instrumentation was installed during the summer of 1985 and was removed by June 1988, although basic monitoring will continue into the 1990's.

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[1] Sierra Nevada Aquatic Research Laboratory, University of California, Star Route 1, Box 198, Mammoth Lakes, CA 93546.

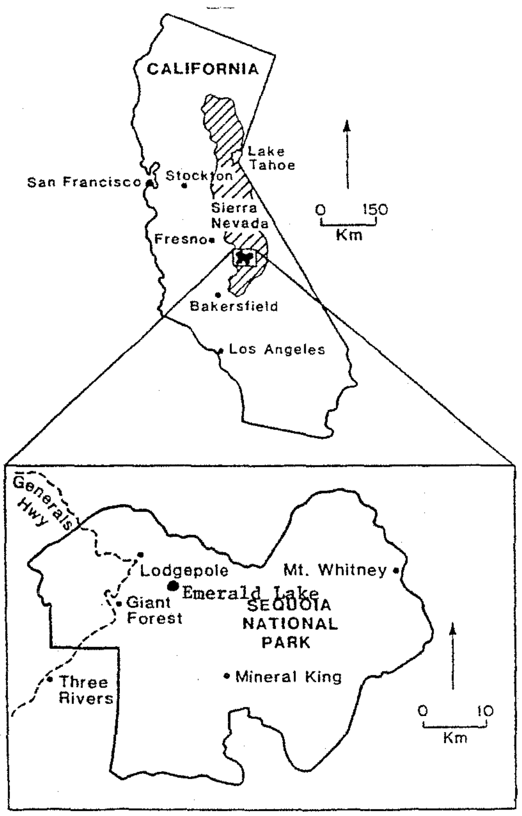

Figure 1. The Emerald Lake basin is in Sequoia National Park.

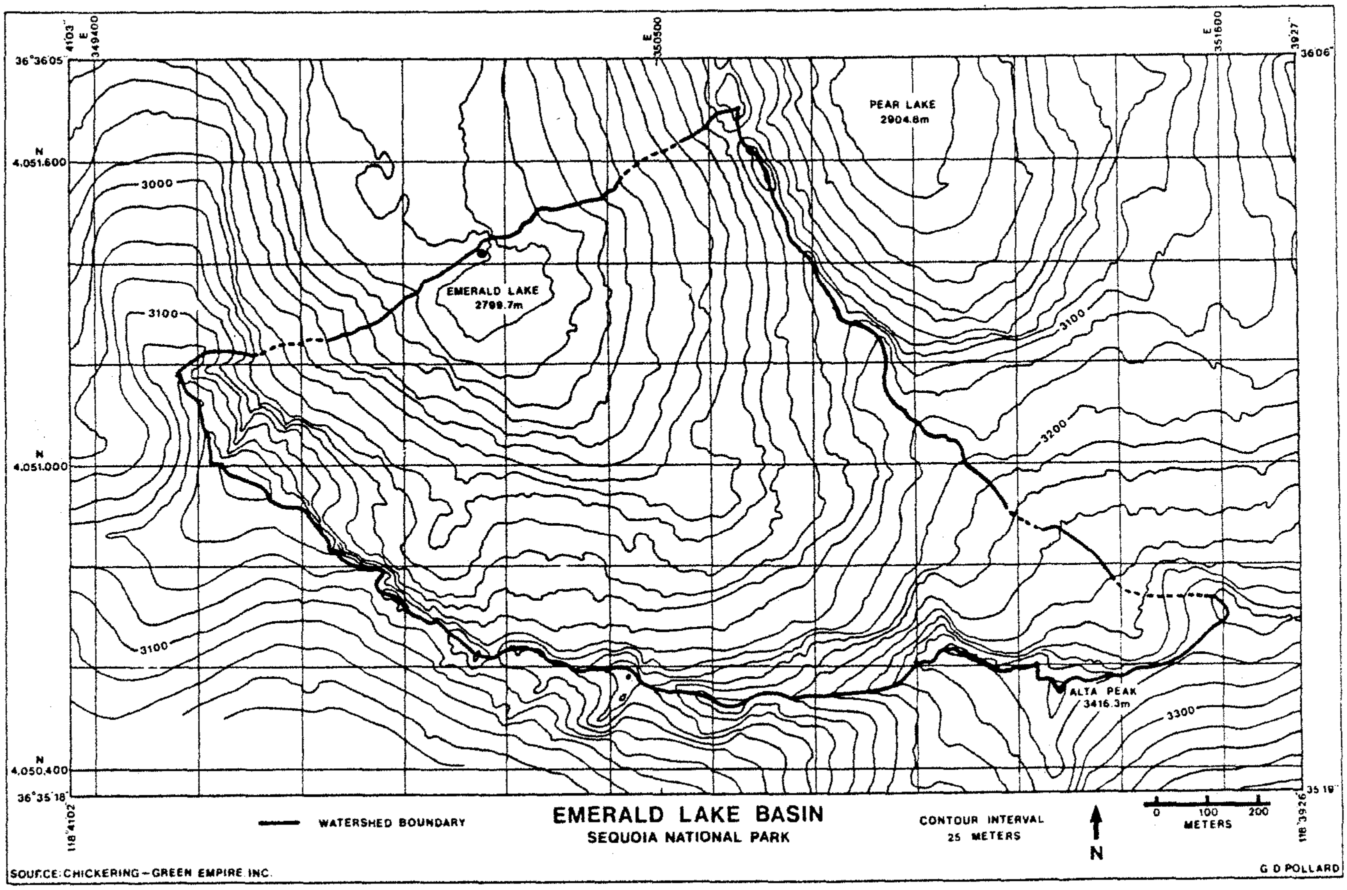

Figure 2. The topography of the Emerald Lake basin is steep and rugged.

CLIMATE

Measurements of several meteorological variables at Emerald Lake provide the first detailed description of the climate of an alpine site in the Sierra Nevada. Precipitation and temperature data have been collected at a few sites in the Sierra, and snowpack water equivalence has been monitored throughout the higher-elevation parts of the range. However, comprehensive evaluation of the climate of an alpine catchment had not been attempted before the Air Resources Board study at Emerald Lake. Although this study did not last long enough to provide information on long-term variations of weather elements, the records from three to five years illustrate general conditions occurring in an alpine basin of the Sierra Nevada. The three water years of detailed study (1986-1988) happened to include one of the wettest winter months on record, three of the driest months on record and one unusually warm and wet spring. Snowpack depth and precipitation were measured throughout the basin, and air temperature, humidity, radiation, and wind speed were measured at two principal stations in the basin. Details about measurement procedures may be found in the project summary report (Dozier, et al., 1989). The micro-meteorological data were essential in estimating various components of the hydrologic cycle, such as snowpack energy balance, snowmelt, snowpack sublimation, lake evaporation, and evapotranspiration. They also permit a general comparison of climatic conditions at Emerald Lake to other environments.

The Sierra Nevada in general and the Emerald Lake basin in particular are influenced by California's Mediterranean-type climate. Precipitation is highly seasonal with about half of the annual amount concentrated in the winter months of December through February and another third in March through May (Stephenson, 1988). Winter storms are highly variable in intensity, duration, freezing level, and inter-storm intervals (Smith, 1982). Periods between winter storms can last from days to weeks and often allow air temperatures to rise above freezing, at least at lower elevations (Miller, 1955).

At Emerald Lake, precipitation amounts from individual winter storms varied from a trace to more than a meter. Annual precipitation was also highly variable. About 260 cm of precipitation was recorded at Emerald Lake in water year 1986 while only about 100 cm fell in water year 1987. An isohyetal map of California (Rantz 1969) indicates the area receives 90-100 cm of precipitation on the average. During the study period from 1985 to 1988, more than 95 percent of the precipitation was snow. A longer-term analysis (Stephenson, 1988) suggests that this elevation zone in the southern Sierra receives between 75 and 90 percent of its precipitation in the form of snow.

Mean daily air temperatures during the study period were usually between -4 and +4 ^{o}C in winter and -1 and +5 ^{o}C in spring. Temperatures in January averaged about -1 ^{o}C. Air temperatures fluctuated dramatically during winter with the passage of different air masses. Minimum temperatures fell below -20 ^{o}C twice during the study, but maximum temperatures above +10 ^{o}C also occurred during almost all winter months. The short period of record suggests that the Emerald Lake basin tends to be warmer than the few other alpine regions of the western U.S. where temperature records are available.

Mean monthly relative humidity was about 75 percent in the winter and about 50 percent in the spring. In winter, the atmosphere has a small capacity for water vapor because of the low temperatures, but what little water vapor is present will be a large fraction of the amount at saturation.

The Emerald Lake basin was subject to strong winds during and shortly after storms. These winds redistributed the snow into a highly variable snow cover (Elder, et al., 1989). During non-storm periods, winds were generally characterized as mild. Long-term average wind speeds measured near Emerald Lake were about 4 $m\ s^{-1}$ and about 6 $m\ s^{-1}$ at a site on the east ridge of the basin. Such wind speeds are comparable to those reported at three alpine sites in Colorado (c.f., Dozier, et al., 1989).

The alpine radiation regime is a critical influence on snowpack development. The relative aridity and clarity of the air permit both high short-wave input and high long-wave loss on a daily cycle. Energy balances differed greatly in spring between slopes exposed to or shaded from sunlight. Shading of the basin changes dramatically as the solar zenith angle changes seasonally. At the winter solstice, Emerald Lake itself receives only a few minutes of direct insolation. In the spring, the sun is much higher in the sky, and shading is greatly reduced. Reflected radiation from nearby terrain also adds to the radiation measured near the lake. During the spring, solar radiation (0.3 to 2.8 μm) accounted for about half of the total irradiance and thermal infrared radiation

(3.5 to 50 µm) made up the other half. Monthly totals of irradiance for the period of April through June were comparable between years to within 10 percent (Dozier, et al., 1989).

SNOW ACCUMULATION

Small storms during autumn initiated the development of the seasonal snowpack. Although most of this early snow melted within a few days after deposition, some of it remained in well-shaded parts of the upper basin. As the basin received less solar radiation with the approach of winter, the ground lost heat and subsequent snowfall was more likely to remain unmelted. A snowpack with an average water equivalence of at least 10 cm over the basin was in place by mid-November, 1985 and early December, 1987. However, snow cover remained shallow and discontinuous in the 1987 water year until January 10. This delay in the beginning of an insulating snow cover allowed the soil to freeze and ice to block the stream channels.

After snow cover was established, snowpack development progressed with successive storms, although the temporal distribution of precipitation was greatly different between the winters. Four of the five winters from 1984 to 1988 were notable for at least one very dry month. Monthly precipitation values throughout most of California were among the lowest amounts on record in each of January 1984, January 1986, November 1986, December 1986, and February 1988. At Emerald Lake, precipitation was less than 2 cm in each of these months except for January 1986, when it was 10 cm. These months provide examples of the mid-winter drought period that can be expected in most winters in the Sierra Nevada (Smith, 1982). At the other extreme, the massive storms of February 1986 deposited almost twice the snowfall of the entire winter of 1987. In a ten-day period, about 1.2 meters of snowfall water equivalence was deposited at Emerald Lake. Much of this snow was redistributed by avalanches (Williams and Clow, these proceedings) as commonly occurs in the steep terrain of the Emerald Lake basin (Elder, et al., 1989).

Virtually all of the winter precipitation observed during the study fell in the form of snow. Only three rain events occurred during the winter months, and rainfall amounts were less than 5 mm in each case. However, the rain-snow level was often only a few hundred meters below the elevation of Emerald Lake (2800 m). Mixed rain and snow events occurred during autumn and spring periods. Thunderstorm activity occurred during the spring of both 1987 and 1988. Precipitation during the months of April through June contributed between 1 and 20 percent of each year's total precipitation. Snowfall in the spring retarded the rate of snowmelt by temporarily increasing the albedo of the snowpack.

In an environment such as the Emerald Lake basin, snow accumulates throughout the winter and does not begin significant melting until spring. The snow cover in early April, prior to the onset of sustained snowmelt, represents the cumulative precipitation for the winter (after adjusting for sublimation and minor midwinter melt). Therefore, intensive snow surveys (depth from 100-300 points and average density from several snowpits) were used to estimate accumulated winter precipitation over the entire basin (Elder, et al., 1989). The average basin-wide snowpack water equivalence at the onset of spring snowmelt was about 200 cm in 1986, 60 cm in 1987, and 63 cm in 1988. The 90 percent error bounds calculated for these snow surveys were about +/- 10 percent in each year. Sublimation was about 20 cm and midwinter melt was about 5 to 10 cm in each year. For comparison, average (since 1930) April 1 snowpack water equivalence at the nearby Panther Meadows (2620 m) and Giant Forest (1950 m) snow courses was 91 cm and 43 cm, respectively. At these same sites, amounts were 172 cm and 13 cm in 1986, 47 cm and 9 cm in 1987, and 40 cm and 0 in 1988.

Evaporative losses from the snow surface appear to be substantial in this region. Sublimation was calculated by adapting a series of equations for estimating turbulent transfer of energy and mass presented by Brutsaert (1982). These computations are described in detail by Marks (1988) and Dozier et al. (1989). The procedure used has a strong physical basis, but has not been verified for snow to the same extent as energy-balance estimates of evaporation from free-water surfaces. Sublimation was calculated as an average flux from measurements at two micro-meteorological stations and then as a total volume after adjusting for snow covered area. Calculated sublimation was typically between 1 and 2 mm per day with extremes related to high vapor pressure gradients and high winds. Monthly total fluxes varied inversely with storm duration. Evaporative losses from snow were the largest component of evaporation in the annual water balance, accounting for about 80 percent of the total quantity. Sublimation was estimated to be about 22 cm in water year 1986 (16 percent of annual precipitation) and about 19 cm in water year 1987 (23 percent of annual precipitation).

SNOWPACK CHARACTERISTICS

Snowfall densities measured on snow boards after an event covered the usual range of 50 to 200 kg m^{-3}. Snowpack densities were generally below 400 kg m^{-3} and often below 300 or 350 kg m^{-3} prior to the introduction of melt water. As expected, snowpack densities remained low later into the year in the shaded areas not subject to sluffs or avalanches. After melt water began to flow through the snowpack, densities increased rapidly to more than 450 kg m^{-3}. Snowpack densities were particularly high throughout the 1986 season, even exceeding 600 kg m^{-3} in the summer.

Snowpack temperatures generally followed a gradient from near-freezing at the base to -6 to -8 ^{o}C near the surface from January through March. The bulk of the snowpack tended to be in the -2 to -4 ^{o}C range. The near-surface layers (top 10 to 20 cm) often had steep temperature gradients and occasionally dropped below -10 ^{o}C. The snowpack generally warmed appreciably in March following an increase in air temperature but still before liquid water entered the snow. Snowpack temperatures were colder than those reported at the Central Sierra Snow Laboratory (McGurk, 1983) but slightly warmer than those monitored at Mammoth Mountain.

Liquid water content was measured with a dielectric probe designed by Armin Denoth and was found to be highly variable throughout the basin, within a single snowpit, between days, and over the course of a day. Residual water content after nighttime drainage was generally within the range of 1 to 3 percent by volume. Averages over a snowpit profile even in the afternoon of days with active melt tended to be in this same range. Individual layers where flow was restricted and water was concentrating had liquid water contents above the meter's maximum sensitivity of 10 percent by volume.

The general stratigraphy of the snowpack at Emerald Lake was not always as obvious as in snowpits at lower elevation. Because the snow surface often did not melt during inter-storm periods, such surfaces did not necessarily stand out. Wind redistribution of snow also greatly altered the snowpack structure between pits only a few meters apart. For example, particular layers might differ in thickness by 10-20 cm between nearby profiles. Wind crusts were often evident in the snowpits and often became ice layers after the introduction of liquid water which tended to accumulate in such layers. The night freeze depth in spring was usually between 5 and 15 cm -- the same range measured at the Central Sierra Snow Laboratory in a forest opening (Kattelmann, 1986).

SNOWMELT

Relatively little snowmelt occurs during the winter season in predominantly north-facing, alpine basins such as Emerald Lake because of the negative radiation balance. When the snowpack forms early in autumn, residual ground heat from summer melts a minor amount (up to a few centimeters) of snow in the early part of winter. In a winter with a late-forming snow cover such as water year 1987, most of this ground heat is lost before a snowpack is in place and geothermal melting is negligible. A small portion of the Emerald Lake basin had a somewhat southerly exposure (Figure 2), and some snow melted on these slopes during interstorm periods. Slopes of other headwater basins across the Marble Fork of the Kaweah River faced directly south and were often observed to be bare of snow in winter after several clear days. The portions of the Emerald Lake basin that were in shade almost continuously did not even form a thin melt crust after extended periods without snowfall.

As winter storms decreased in magnitude and frequency, snowmelt began in successive portions of the Emerald Lake basin as solar zenith angles decreased, terrain shading decreased, and the local radiation balance became positive. The fraction of the basin where snow was melting steadily increased from mid-March through mid-May, except when interrupted by storms. The first signs of sustained snowmelt runoff in small streams were observed between March 19 and 30 in 1986, 1987, and 1988 (Figure 3), although melt in 1986 did not really accelerate until mid-April. In 1984 and 1985, the initial rise of the snowmelt hydrograph was delayed until the last week of April. Melt rates increased throughout the spring as the radiation input increased. Average basin-wide snowmelt peaked when the increase of snowmelt was balanced by the decline of snow covered area.

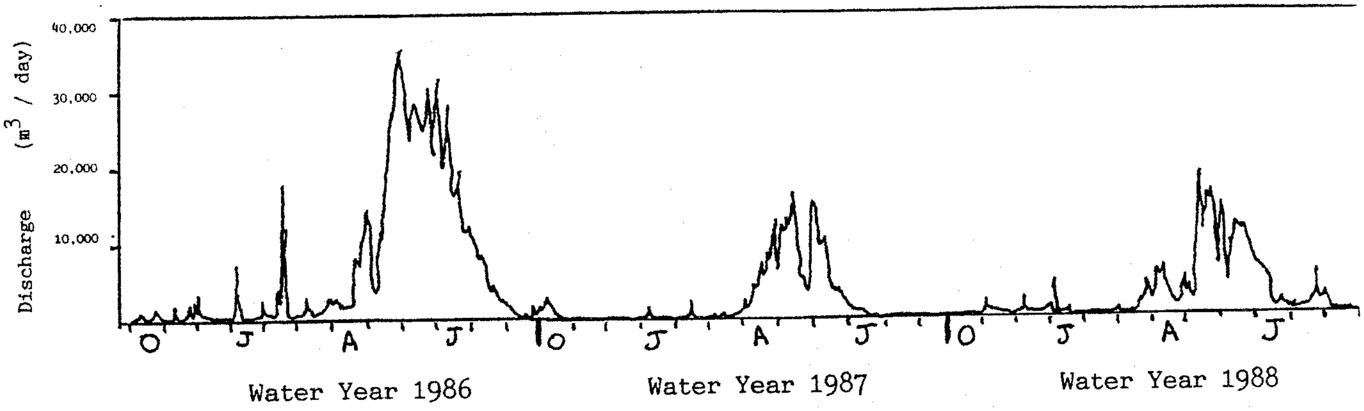

Figure 3. Streamflow was strongly concentrated in the April-July snowmelt period.

This peak of average snowmelt occurred in mid- to late May in 1984, 1987, and 1988, and was delayed until the end of May or early June in 1985 and 1986. Snowmelt both becomes substantial and peaks between 2 and 4 weeks later in basins such as Emerald Lake than in south-facing basins or those at low elevation. Areas of Sequoia National Park below 2200 m had generally lost their snow cover a week or more before snowmelt peaked at Emerald Lake.

Throughout the spring snowmelt seasons at Emerald Lake, snowmelt varied greatly around the basin throughout each day as the local terrain-sun geometry changed. The spatially-distributed snowmelt regime is currently (spring 1990) being modeled at the University of California-Santa Barbara by Li Shusun and Jeff Dozier (Dozier, 1988). Until this work is completed, our best estimates of snowmelt around the basin were developed from a network of 50 ablation stakes. These stakes were measured at irregular intervals of 4 to 8 days and showed which portions of the basin were generating snowmelt at various rates throughout the season. Over the entire basin, daily snowmelt averaged over the measurement intervals ranged from 1 to 1.5 cm of water equivalence per day in April and May and up to 3 cm of water equivalence per day in June and July. Rates were obviously higher than these averages in portions of the basin with above-average exposure to sunlight and were smaller than these values in the deeply shaded parts of the catchment. Snowmelt rates were greatest when insolation on a surface was high, albedo was low, snow was thin enough to allow penetration of radiation to the ground, and nighttime freezing was negligible.

Snow covered area determined the volumes of snowmelt and sublimation given the average fluxes of these processes. Snow covered area was estimated from a combination of aerial and ground-based photographs obtained at intervals of 7 to 14 days. Snow cover was mapped from the photographs, and the combined area of snow fields and snow patches was estimated from the maps. After the final snow storm of the season, snow covered area declined rapidly (Figure 4). Snow covered area declined from 60 percent of the basin to 20 percent at the rate of approximately 1 percent per day. Because of the considerably greater snow depth in 1986, snow cover was depleted at a slightly slower rate in 1986 than in 1987 even though equivalent snow covered area occurred a month later in 1986 than in 1987 (Figure 4). In 1986, the last fifth of the basin was uncovered at a slow rate because this fraction consisted of deep deposits of avalanche debris and drifts in well-shaded locations. This snow from 1986 remained in about a tenth of the basin into the late summer of 1987.

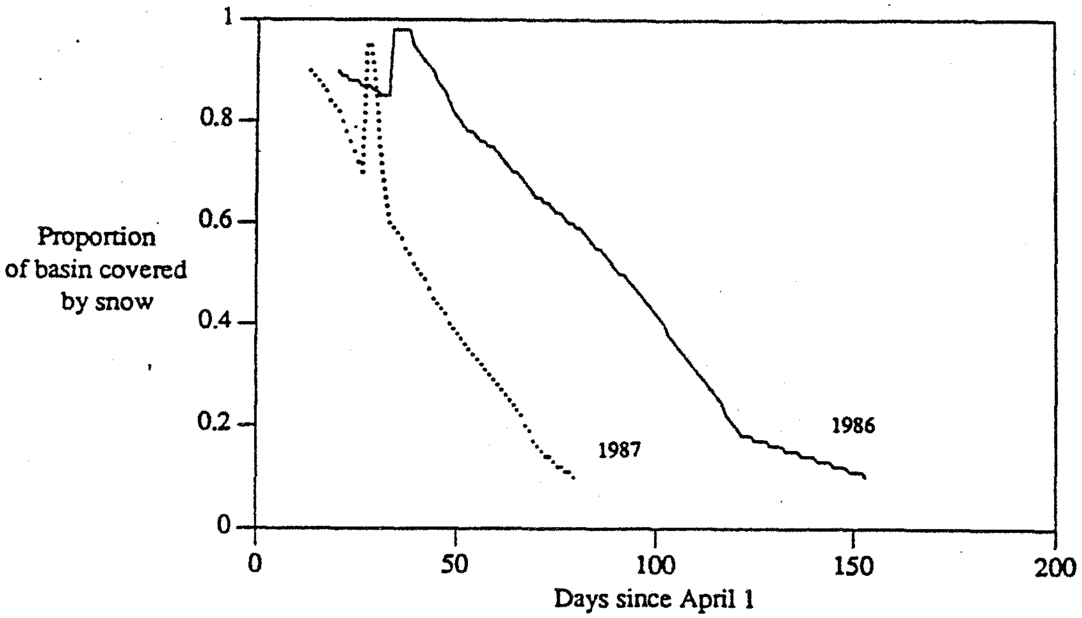

Figure 4. Depletion of snow covered area occurred 4 to 5 weeks later in 1986 than in 1987.

RUNOFF GENERATION

Transformation of snowmelt into streamflow involves thermal, capillary, and conveyance properties of the snowpack; soil-snow interactions; hydraulic properties of the substrate; and the stream channel network. At Emerald Lake, none of these considerations caused excessive losses or delays in runoff production. As noted above, the snowpack was only a few degrees below freezing in most of the basin and required only a couple of centimeters of meltwater to satisfy the seasonal heat deficit. For example, a 2 m deep snowpack of 500 kg m^{-3} at -5°C requires about 3 cm of water to be warmed to 0°C. On a daily cycle, the night freeze deficit requires energy that would otherwise melt 1-3 mm of water equivalence. After a portion of the snowpack is warmed to the melting point, a small quantity of water is held against gravity between the grains by capillary tension. Measurements of residual liquid water content after drainage can approximate this "irreducible water content" (Colbeck, 1978). As noted above, liquid water contents after nighttime drainage in the Emerald Lake basin were generally between 1 and 3 percent by volume. Although these storages must be satisfied eventually for the entire snowpack, they need only be satisfied locally for water to migrate along an isolated path toward the base of the snowpack. In the early stages of snowmelt, liquid water was commonly found near zones of subfreezing snow in several snowpits.

After water is available for percolation, it moves through the pack at relatively slow speeds (0.04 to 1.8 m per hour) depending on the permeability of the snowpack and the rate of water input. Inhomogeneities in the snowpack such as ice layers or zones of enhanced permeability complicate the process. Virtually the entire range of flow features of natural snowpacks described in the literature such as flow fingers, ice lenses and columns, surface depressions and rills, and macropores was observed in the snow cover at Emerald Lake.

After melt water is released from the base of the snowpack, it can take a variety of paths to stream channels. At Emerald Lake, much of the water flowed over impermeable or saturated surfaces and had little contact with geologic materials. As the snow cover disappeared, overland flow was observed downslope of virtually all snow patches. When water inputs were low, a greater proportion of water probably flowed through the soils rather than predominantly over them as during most of the spring when they were assumed to have been saturated. Formation of extensive basal ice at the snow/ground interface such as during winter of 1987 would also minimize the contact of meltwater with soils. The channels themselves were also clogged with ice in 1987, and water was forced to follow new pathways downslope. Channels were not eroded in the basal snow as quickly as necessary in 1987, and the entire snowpack became saturated in areas where water concentrated leading to localized oversnow flow.

Because routing of meltwater through soils does not appear to be important during the snowmelt season at Emerald Lake and the channel network is simple and efficient, hydrographs of the small tributaries to Emerald Lake can approximate the average release of water from the snowpack. These hydrographs were used to examine changes in lag time due to snowpack routing. Both the beginning of the daily rise in the hydrograph and the peak of the hydrograph occurred at progressively earlier times in the day as the snowpack matured and became shallower. The daily hydrographs began to rise about 1600 in the early melt season and advanced to about 1000 near the end of the melt season. The hydrographs peaked about 0400 on the following morning in 1986 and around midnight in 1987 at the beginning of each season. The time of these peaks progressively advanced to about 1800 near the end of each season. Peak wave speeds, the time lag between peak surface melt and peak outflow from the snowpack, as averaged over the basin were estimated to be about 0.2 to 0.6 m per hour in the two years. Additional information about snowpack water routing at Emerald Lake will be developed in a subsequent paper.

STREAMFLOW

Streamflow out of the Emerald Lake basin was strongly concentrated during the spring snowmelt period (Figure 3). More than three-quarters of the annual runoff occurred in the months of April through July. May and June were the two months of greatest flow, accounting for at least half of the volume in each of the five years. Typical flows during the peak of snowmelt ranged from 10,000 to 30,000 m^3 per day. Streamflow exceeded 10,000 m^3 per day (0.75 cm per day water depth averaged over the basin area) on 71 days in 1986 versus 32 days in 1987, 26 in 1988, 24 in 1984, and 20 in 1985. Flows were above 20,000 m^3 per day (1.5 cm per day) on 44 days during spring and summer of 1986. The highest daily volume of record was about 36,000 m^3 on May 30, 1986. Instantaneous flows rarely exceeded 0.5 m^3s^{-1} under snowmelt conditions. Under optimum combinations of conditions favoring high rates of snowmelt described above in the snowmelt section, peak discharges approached 1 m^3s^{-1} during 3 days in 1986. However, such conditions were rare during the study period, and instantaneous and daily peak flows in the other four snowmelt seasons were barely half of those observed in 1986.

Streamflow in the winter months was a small proportion of that occurring in the spring and was usually less than 500 m^3 per day. Midwinter streamflow generally receded as groundwater discharge and snowmelt from ground heat declined. The smallest midwinter flows were less than 20 m^3 per day. Some of the streamflow out of the basin during winter resulted from the displacement of lake water by snowfall and avalanches on to the lake. This displacement flow provided an excellent record of the timing of winter snowfall. Analysis of the flow volumes may also provide an index of the quantity of snowfall. Volumes of water displaced from the lake by avalanches were substantial and caused all of the midwinter peak flows observed in the outflow channel (Figure 3). The greatest instantaneous discharge during the study period occurred on February 15, 1986 when massive avalanches on to the ice cover of Emerald Lake displaced a substantial amount of the water in the lake (Williams and Clow, these proceedings). Peak flows between 10 and 20 m^3s^{-1} were estimated from channel scour.

The annual volume of water flowing out of the Emerald Lake basin over the period of record (October 1983 to September 1988) ranged from 670,000 m^3 to 2.6 million m^3 or more than a three-fold difference between the minimum year of 1985 and the maximum year of 1986. The equivalent depths of water averaged over the basin area of 1.2 km^2 were 90 cm in water year 1984, 60 cm in wy 1985, 210 cm in wy 1986, 70 cm in wy 1987, and 80 cm in wy 1988. These estimates in combination with estimates of annual precipitation permit a simple evaluation of the runoff efficiency of Emerald Lake as about 80 percent in 1986 and about 67 percent in 1987 and 1988. The peak snowpack water equivalence before the onset of spring melt is perhaps a more useful point of reference for alpine hydrology. In the years 1986, 1987, and 1988, about 90, 75, and 80 percent of the water stored in the snowpack plus subsequent precipitation became streamflow, respectively.

SUMMARY AND CONCLUSIONS

Hydrologic and meteorologic observations at Emerald Lake in Sequoia National Park over a five-year period provide the first detailed description of the snow hydrology of an alpine basin in the Sierra Nevada. Although most of the properties and processes occurring in the alpine zone could be inferred from studies and streamflow records at lower elevation and the scattered snow measurements at high elevation, the Emerald Lake study confirmed, quantified, and expanded on many of our assumptions. As expected, the precipitation and runoff regimes are highly seasonal. The snowpack generally begins to develop in November but can be delayed into January. Virtually all winter precipitation at this elevation falls as snow, but rainfall is possible. Monthly precipitation during the winter can range from 0 to more than 1 meter. Prolonged periods between storms permit sublimation losses to exceed 20 cm per winter, but little or no melt occurs during the winter in basins with northern exposure. Seasonal snow storage prior to spring melt ranged from 60 to 200 cm water equivalence.

Sustained snowmelt runoff began in mid- to late April and generally peaked about a month later. Average basin-wide snowmelt was about 1 to 1.5 cm per day in April and May and up to 3 cm per day in June and July. More than 75 percent of the annual streamflow occurred from April through July. Peak snowmelt runoff exceeded 0.75 cm per day on at least 20 days per year. Instantaneous discharges rarely exceeded 0.5 $m^3 s^{-1} km^{-2}$. More than 75 percent of the peak snowpack water equivalence and spring precipitation became streamflow.

The streamflow record was the most useful single source of information in this study. Unfortunately, almost all of the original streamgages at high altitude in the Sierra Nevada have been discontinued in recent decades. New gages on headwater streams established under projects of the California Air Resources Board and NASA Eos Program will help to relieve this basic deficiency in our collective monitoring and research efforts concerning the hydrology of the Sierra Nevada.

ACKNOWLEDGEMENTS

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