Snowmelt runoff and water yield along elevation and temperature gradients in California’s southern Sierra Nevada

Carolyn T. Hunsaker, Pacific Southwest Research Station, USDA Forest Service, Fresno, CA

Thomas W. Whitaker, Pacific Southwest Research Station, USDA Forest Service, Fresno, CA

Roger C. Bales, Sierra Nevada Research Institute, University of California, Merced, CA

Correspondence:
Dr. Carolyn Hunsaker
Pacific Southwest Research Station
2081 E. Sierra Avenue
Fresno, CA 93710
559-323-3211
chunsaker@fs.fed.us

1Current address: Infinity Wind Power, Santa Barbara, CA
Abstract:

The hydrologic responses of eight headwater catchments—the Kings River Experimental Watersheds—located across the rain-snow transition in the southern Sierra Nevada were investigated over 4 years using continuous streamflow, precipitation, snowpack, and meteorological-station data. At the highest elevations, annual precipitation was 75 to 95% snow, versus 20 to 50% at the lowest elevations. Average temperature was 1 to 2°C warmer in the lower versus upper elevation catchments, with daytime temperatures accounting for most of that difference. About 80 to 90% of the precipitation occurred in December through April, with snow present for the 6-month period from early December through early June at the higher elevations, and the 4-month period from early January through early May at the lower elevations. Peak discharge lagged peak snow accumulation on the order of 60 days at the higher elevations and 20 to 30 days at the lower elevations. Runoff at the higher elevation catchments consistently lagged that at the lower by about 30 days; in any given catchment, interannual variability accounted for a 30-day difference in timing. Snowmelt dominated the diel streamflow cycle over a period of about 30 days in higher elevation catchments, followed by a 15-day transition to evapotranspiration dominating the diel streamflow cycle. Discharge from lower elevation catchments was rainfall dominated in spring, with the transition to evapotranspiration dominance being less distinct. Lags in the system between peak temperature and peak snowmelt were consistent at about 3 to 6 hours. Water yield increased with elevation, associated with lower vegetation density, coarser soils and a shorter growing season at higher elevations. Climate warming that results in a longer growing season and a shift from snow to rain would result in earlier runoff and lower water yield. Sustaining or enhancing water yields in these mixed-conifer forests will require management of evapotranspiration by reducing vegetation density, and using thinning patterns that attenuate snowmelt.

KEY WORDS  hydrology, meteorology, Sierra Nevada, headwaters, mountains
INTRODUCTION

The rain-snow transition zone in forested, Sierra Nevada catchments experiences a range of seasonal changes that depend on winter and spring temperature and precipitation patterns. The lower end of this zone experiences rain more often than snow, with the upper elevations generally dominated by seasonal snow that undergoes spring melt over a relatively short period. As snow melts, the zone undergoes seasonal changes, going from a snow-covered water-saturated state with modest evapotranspiration to a system dominated by evapotranspiration to a relatively dry state over a period of several weeks.

Numerical simulations suggested that for physiographically heterogeneous basins, such as in mountainous topography, spatial variations in available soil water can have significant effects on areally averaged carbon and water flux rates, particularly under drying conditions (Band, 1993). Carbon exchange and evapotranspiration have been observed to shut down during both dry summer periods (Brown-Mitic et al., 2007) and cold winter periods (Monson et al., 2005). The southern Sierra Nevada is a Mediterranean climate, so it experiences relatively wet winters and dry summers.

Vegetation has a large effect on the water budget through both transpiration and interception, with an inverse relation between forest cover and streamflow demonstrated for many forested landscapes (Bosch and Hewlett, 1982; Trimble et al., 1987; Calder, 1998). Because water may reach the stream channel through both surface and subsurface pathways (Dunne, 1978), the explicit mechanism of streamflow generation must be known for the role of forest vegetation to be quantitatively understood. That is, water that passes rapidly to stream channels during heavy rainstorms or persistent, early spring snowmelt has less opportunity to be affected by evapotranspiration; whereas a greater fraction of lighter rain or later snowmelt when the growing season is underway should be returned to the atmosphere as evapotranspiration.

In a recent review of paired-catchment studies involving forest regrowth, it was observed that for snow-affected catchments, the largest absolute decrease in runoff resulting from regrowth occurred during snowmelt, but the largest proportional difference in runoff was in summer (Brown et al., 2005). In contrast, the largest absolute decrease in winter-rain-dominated catchments was earlier, in winter months, when rainfall was
above the monthly average. Streamflow changes resulting from regrowth were driven by both interception and evapotranspiration changes.

The goals of the research reported here are: 1) to define the differences in hydrologic response across a 700-m elevation range involving a transition from a mixed rain-snow temperature and precipitation regime to a snow-dominated regime, as apparent in continuous precipitation, snowpack, and streamflow measurements, and 2) to infer how future changes in temperature and forest density may affect that response.

METHODS

The eight forested catchments that were studied make up the Kings River Experimental Watersheds (KREW), a watershed-level, integrated ecosystem project for long-term research on nested headwater streams in the southern Sierra Nevada (Figure 1). The KREW study is operated by the U.S. Department of Agriculture’s Pacific Southwest Research Station, which is part of the research and development branch of the Forest Service, under a long-term (50-year) partnership with the Forest Service’s Pacific Southwest Region. The purpose of KREW is to document the variability in headwater ecosystems of the Sierra Nevada, and to address forest-land-management issues; it was established in 2000 (www.fs.fed.us/psw/programs/snrn/water/kingsriver).

The catchments range in size from 49 to 228 ha (Figure 1), and have mean elevations ranging from 1830 to 2410 m (Figure 2). Each catchment spans 200 to 400 m in elevation from top to outlet. The four lower elevation catchments (P301, P303, P304, D102) and B201 are largely in Sierran mixed-conifer forest (76 to 99%), with some mixed chaparral and barren land cover (Figure 1). Sierran mixed-conifer vegetation in this location consists largely of white fir (Abies concolor), ponderosa pine (Pinus ponderosa), Jeffrey pine (Pinus jeffreyi), sugar pine (Pinus lambertiana) and incense cedar (Calocedrus decurrens). The other catchments are also dominated by Sierran mixed-conifer forest (47 to 78%), but contain a larger amount of red fir (Abies magnifica) (19% in T003 and 41 and 44% in B204 and B203, respectively). All watersheds have some meadow except P303. The meadow influence on stream channels varies widely; in B201 92% of the channel borders meadow while only 2.5% of the D102 channel borders meadow. The higher-elevation stream channels have more adjacent meadow than the
lower-elevation channels, and some of these high-elevation meadows are fens. Soils are derived from granite. Shaver and Gerle-Cagwin soils dominate the four lower-elevation catchments, and the colder, Cagwin soils dominate the four higher-elevation catchments (Sierra National Forest, 1983). The dominant aspect for most of the watersheds is southwest. The aspect of P304 is half northwest and half southwest. Teakettle, T003, is the most variable in aspect with south and east directions dominant.

Each of the streams draining seven catchments have two Parshall-Montana flumes, a large flume (30- to 122-cm throat width) for measuring high flows and a smaller one (throat widths 8 to 15 cm) for measuring moderate and lower flows. The Teakettle stream has a historic weir with a metal 90° V-notch for low flows and a Cippoletti for high flows. The primary stage-measurement instrument is an air bubbler (ISCO™ 730), and electrical-pulse devices (Aquarod™) and pressure transducers (Telog™) provide backup measurements. Discharge data are audited by cross checking with manual stage readings and adjustments are made if needed. The bubbler data in the small flume produced 90% of the annual hydrograph values, with backup measurements used when drift in the signal from the air bubbler was observed. Data from the large flume are manually spliced into the record when the water level is within 7.6 cm of the top of the small flume. All KREW data are reported for water years: October 1 through September 30. Daily precipitation and stream-discharge values that have been quality assured are available for site code KEW at http://lterweb.forestry.oregonstate.edu/climhy.

Four meteorological stations are located at the low and high elevations in both the Providence (1,750 and 1,984 m) and Bull (2,194 and 2,462 m) sets of catchments (Figure 1). Stations were positioned at the center of clearings with a diameter at least as wide as the height of the trees surrounding the clearing. Larger clearings were not available in the forest. Snow pillows (Mendenhall Manufacturing) exist at the upper Bull and upper Providence meteorological stations; all four stations have acoustic snow-depth sensors (Judd Communications™) mounted 5 m above the ground. Each snow pillow consists of four 1.2- by 1.5-m rectangular, steel bladders positioned adjacent to each other on ground with less than 5% slope, filled with an antifreeze solution, and plumbed together to form a 2.4-by 3-m pillow. This design is the same as that used by the California Snow Survey.
A Sensotec™ pressure transducer measures pressure exerted on the pillow by overlying snow.

Precipitation is collected using Belfort™ 5-780 rain gages equipped with load cells (Tedea-Huntleigh™ 1042), mounted 3 m above the ground on large wooden posts. Each gage uses nontoxic, propylene-glycol antifreeze that allows for measurement of snow. In addition, a mineral-based oil layer is used to cover the liquid in the gage to help prevent evaporation. The collection orifice is encircled by an Alter-type windshield (Novalynx™ 260-952). Temperature sensors (Vaisala™ HMP45C) are in standard enclosures, mounted 4 m above the ground on a 6-m triangular tower. The anemometer for wind measurements (Met One™ 013A) is mounted 7 m above the ground. Meteorological measurements are logged as 15-minute averages (Campbell™ CR10x), except for precipitation, which has 1-minute averages. Each 15-minute average is the mean of 360 samples taken at 2.5-second intervals. For the current analysis, hourly averages of temperature and wind speed were used, with gaps in data filled by either adjacent duplicate sensors, correlation with other KREW meteorology stations, or interpolation.

RESULTS

For a given year, precipitation amount and timing were the same for all four weather stations despite the nearly 700-m difference in elevation from the lowest to highest stations (Figure 3). Precipitation amounts were not corrected for wind influence because daily windspeeds averaged around 1 m/s and were seldom above 2 m/s (Figure 4). At 1 m/s the wind corrections for rain and snow for an Alter-shielded gage would be under 5%; at 2 m/s the corrections would be about 7 to 10% (Yang et al., 1998). Based on longer-term (70-yr) precipitation records from a southern Sierra Nevada site, Grant Grove in Sequoia National Park, precipitation in water years 2004 and 2007 was 60-70% of the mean, with 2005 and 2006 being about 135% of the mean (data available at Western Regional Climate Center).

The fraction of precipitation that fell as snow ranged from 75 to 90% at the upper Bull weather station and from 35 to 60% at upper Providence (Figure 3). Snow-depth sensors at the four sites clearly showed that upper Bull had more snow than the other sites; lower Providence had the least snow in most years (Figure 5). Snow water
equivalent measurements usually peak at the same time each year for the two locations, but the difference snow can make is accentuated in the 2007 dry year (Figure 3). As little as 20% of the annual precipitation at lower Providence was snow in 2006. Lower Bull and upper Providence showed similar snow depths in most years (Figure 5). The snow and rain measurements are collected several meters apart, and although individual snow-depth measurements show considerable spatial variability (Molotch and Bales, 2005), they can illustrate general trends.

Daily average temperatures measured at upper Bull were about 1 to 2 °C cooler than at lower Providence during the first third to half of the water year, including the snow-accumulation season (Figure 6). Average temperatures for lower Providence (upper Bull) were 7.8±1.4 °C (11.3±0.8 °C) for the 4 years, where ± refers to the standard deviation. This difference is caused mainly by higher daytime temperatures, which were 3 to 4 °C warmer at lower Providence than at upper Bull. Daily maximum temperatures averaged 15.0±1.4 °C (11.6±0.8 °C) for the 4 years at lower Providence (upper Bull). Daily minimum temperatures were 1 to 2 °C warmer at lower Providence during the cold season, but basically the same as upper Bull during the warm season. Minimum values averaged 3.4±0.8 °C (3.3±1.1 °C) for lower Providence (upper Bull). Also of interest is the approximately 11 to 12 °C difference between the daily maximum and minimum at lower Providence versus 8 to 9 °C at upper Bull, reflecting greater daytime heating at the lower site; both sites are cooled by downslope flows at night. The temperatures at both sites illustrate the temperature-limited primary productivity in the catchments, i.e. 30 to 35% of daily minima and 15 to 20% of daily average temperatures at or below freezing.

Streamflow hydrographs for the eight catchments for 2007 show the greater importance of snowmelt at the higher elevations and the greater influence of rain at the lower elevations (Figure 7). Many of the prominent rain events that caused peaks in the hydrographs at the lower elevations generated much smaller peaks in the higher elevation streams, where the snowmelt peak was dominant. This effect is much more distinct in the expanded hydrographs on Figure 8, e.g., days 170, 177, and 215.

The same proportion of annual runoff occurred about 30 to 45 days earlier in the lowest elevation catchment as compared to the highest elevation catchment in both wet and dry years (Figure 9), reflecting the greater proportion of rainfall at lower elevations.
In lower elevation D102 half of the annual discharge occurred by water-year day 160 (Mar 8) in the drier years 2004 and 2007, versus water year day 189 (Apr 6) for higher-elevation B203 in the same years. In the wetter years, the corresponding days for D102 and B203 were 187 (Apr 4) and 230 (May 13), respectively. For a single catchment, there was also a 30 to 45 day difference between dry and wet years for the day when 50% of annual discharge occurred. The hourly hydrographs show two distinctly different periods, one in which snowmelt dominates diel patterns and a later period dominated by evapotranspiration (Figure 8). The time of year when streamflow shifted from being snowmelt dominated to evapotranspiration dominated had a lag of about 30 to 60 days across the elevation gradient of the catchments. At the lowest elevation stream gage (D102) this transition occurred around day 170, but was masked in part by a rain event on days 170-171. The transition occurred a few days later at P304 and P303. At P301, the transition was around the time of the rain event on day 216, and shortly thereafter in B201 and T003. The transition occurred around day 233 at B204 and B203. During the period when snowmelt dominated diel cycles in streamflow, the lag between peak temperature and peak discharge was 3 to 6 hr. For the post-snowmelt period when evapotranspiration dominated diel cycles in streamflow, the lag between peak temperature and peak discharge was 17 to 19 hr, and the lag between peak temperature and minimum discharge was 3 to 6 hr. Lags in the 4 years were similar.

Annual discharge in the eight catchments increased with elevation; however, the relative increase differed in wetter (2005, 2006) vs. drier (2004, 2007) years (Figure 10). Slopes of the best-fit lines are 32, 96, 70 and 12 mm discharge per 100 m elevation for 2004, 2005, 2006 and 2007, respectively.

DISCUSSION

The increase in discharge with elevation across the eight catchments was apparently associated with the greater fraction of precipitation falling as snow and later onset of the spring increase in forest evapotranspiration in the snow-dominated versus mixed rain and snow catchments. The 30- to 60-day earlier transition to evapotransition (Figure 8) across the 600-m mean elevation difference and smaller fraction of days with subfreezing temperatures reflects a significantly longer growing season for the lower elevations.
Also, none of the streamflow records reflect the summer shutdown in evapotranspiration that has been observed for a Ponderosa Pine–Douglas Fir forest in the mountains of Arizona (Brown-Mitic et al., 2007). All eight catchments apparently had sufficient subsurface storage of water to maintain evapotranspiration until the first fall rain, on day 331. The possible exception is P301, which shows a step change in the evapotranspiration signal in streamflow around day 298. However, there was no such change in the other, wetter years, leaving open the possibility of a soil-moisture threshold for the component of evapotranspiration reflected in streamflow. There were no apparent technical low-flow measurement issues, and the record is thought to reflect real changes in flow.

Runoff increasing but precipitation remaining the same across the elevation gradient implies that water yield increases significantly with elevation. Dividing discharge by precipitation shows the water yields to be about 0.10 to 0.35 in drier years and 0.35 to 0.70 in wetter years. The lack of an increase in precipitation with elevation across the nearly 700-m elevation gradient of the meteorological stations was somewhat surprising, but was reproduced over the 4 years of record. It is well established that for a given location, the fraction of annual precipitation that is returned to the atmosphere as evapotranspiration generally decreases as precipitation increases, i.e., annual runoff increases with precipitation (e.g., Zhang et al., 2001). Year-to-year differences in rates of snowmelt and antecedent moisture conditions also affect water yield (Ffolliott et al., 1989). The observed increases in runoff with elevation, ranging from 12 to 96 mm/year per 100-m elevation over the 4 years analyzed, are in the same range as the 60 mm/year average reported by Dingman (1981) for 49 New England catchments.

Soils and vegetation mediate annual water yield through multiple physical and biological water-transfer processes including canopy interception of snow and rain, snow sublimation, water storage in soil, evaporation, and transpiration. Leaf Area Index (LAI) is about 80% higher at the lower elevations (Figure 11). Multiple factors contribute to this difference. The Providence catchments have more understory vegetation, e.g., manzanita (Arctostaphylos), Ceanothus, and lupine (Lupinus), whereas many areas in the Bull catchments have little understory. The Bull catchments have a larger proportion in meadows (2 to 5%) than the Providence catchments. Thus, lower evapotranspiration
throughout the growing season is also a factor in the greater water yield at the higher elevations. This includes: (1) evaporation from soil being greater during the longer snow-free season at lower elevations, (2) sublimation being greater in the denser forest at lower elevation, and (3) transpiration being higher at the lower elevations with higher LAI and a longer growing season (LaMalfa and Ryle, 2008).

Studies of water yield across elevation differences in mountain catchments and corresponding differences in snowpack and vegetation density have not been reported. However, it is useful to compare the current results with those from studies involving vegetation changes with time. It is well established that reduction in vegetation through timber harvesting increases water yield, and that afforestation decreases water yield, although results are highly variable and changes in water yield are generally detectable only after 20 to 30% of a catchment is harvested (Hibbert, 1966; Bosch and Hewlett, 1982; Stednick, 1996; Burton, 1997). Although this topic is much discussed in California, few if any, paired-watershed timber-harvest projects designed specifically for water-yield augmentation have been implemented. Nonetheless, Troendle et al. (2001), who worked in the colder Rocky Mountains, noted that timber harvesting in snow-dominated catchments of the mountain West increases water yield in proportion to the area of the disturbance owing to a reduction in net evapotranspiration, with changes in streamflow occurring on the rising side of the hydrograph and early in the runoff period owing to earlier snowmelt in clearings. Thus the pattern of vegetation as well as the density affect water yield.

Troendle (1983) noted that in snow-dominated, forested catchments, water yields are affected by the energy budget of the forest, which determines the accumulation and melt characteristics of the snowpack, and by the magnitude of evapotranspiration, i.e. amount of vegetation; both can be manipulated by forest management. The impact of harvesting on snow accumulation is significant and is a result of the combined effect of interception loss and alteration of the depositional pattern. The combined effect of both processes during wet years causes efficient increases in water yields that are highly correlated with precipitation input (Troendle and King, 1987). This is consistent with our observation that the increase in runoff with elevation (lower LAI), was much more pronounced in wet versus dry years.
CONCLUSIONS

Small temperature differences between rain- versus snow-dominated catchments across an elevation gradient of 700 m result in significantly different timing of runoff and water yields at in Sierra Nevada mixed-conifer catchments. The approximately 700-m elevation difference in catchments results in daily maximum and daily average temperature differences of 3-4°C and 1-2°C, respectively, and a 30-day difference in the timing of runoff. Thus each 1°C increase in long-term average temperature could represent an earlier runoff in this zone of 7 to 10 days.

A longer growing season and more vegetation in the mixed rain-snow dominated versus higher-elevation snow dominated catchments result in more evapotranspiration and thus lower water yield at the lower elevations. Part of this difference is a long-term product of small climatic gradients, resulting soil formation, and vegetation response in temperature-limited regimes. Both climate warming and forest management have the potential to significantly alter future hydrologic response of Sierra Nevada forested catchments. While there is ample evidence that reductions in LAI, e.g. through forest thinning, controlled burns and wildfire, will result in less evapotranspiration and enhanced runoff, those effects will diminish over time as LAI increases back to levels prior to these perturbations. Sustained management actions would be required to maintain runoff gains from forest thinning or controlled burns. Findings at these southern Sierra Nevada catchments also suggest that gains in water yield can occur in both the mixed rain-snow and snow-dominated forests, though objectives at the snow-dominated elevations should include strategies to attenuate snowmelt as well as reduce evapotranspiration.

The pairing of a set of rain and snow catchments with a set of snow-dominated catchments makes KREW a good location for monitoring and predicting climate change effects on mountainous forest ecosystems in California.

ACKNOWLEDGEMENTS

The establishment of KREW would not have been possible without funding from the National Fire Plan of the USDA Forest Service. Parts of the research received support
from California’s State Water Resources Control Board, through Proposition 50 (the Water Security, Clean Drinking Water, Coastal and Beach Protection Act of 2002), and the National Science Foundation, through the Southern Sierra Critical Zone Observatory (EAR-0725097). Sean Eagan and Jeff Anderson, the first KREW hydrologists, deserve much of the credit for the design and establishment of the flumes and meteorology stations. Sage advice was provided to them by many hydrologists/scientists in the early years, including Randall Osterhuber, Charles Troendle, John Potyondy, and Brian Staab.
REFERENCES


Molotch NP, Bales RC. 2005 Scaling snow observations from the point to the grid element: Implications for observation network design. *Water Resources Research.*


List of Figures

1. Kings River Experimental Watersheds (KREW) catchments and instrument locations. The four Providence catchments in the upper left are at an elevation that receives both rain and snow (P301 99 ha, P303 132 ha, P304 49 ha, and D102 121 ha). The four Bull catchments in the lower right are at an elevation that receives mostly snow (B201 53 ha, B203 138 ha, B204 167 ha, and T003 228 ha).

2. Elevation distributions of the eight catchments and elevations of the four meteorological (met) stations. The meteorological stations are, from lowest to highest, lower Providence, upper Providence, lower Bull, and upper Bull.

3. Cumulative precipitation amounts for the four meteorological stations and snow water equivalent (SWE) for upper Bull and upper Providence stations. The upper Providence snow pillow and the Bull meteorological stations were not active in water year 2004.

4. Distribution of windspeeds at two meteorological stations for water year 2006. Windspeeds at Lower Bull were higher than at the other three stations.


6. Distribution of daily maximum, mean, and minimum temperatures for water year 2006, for lower Providence and upper Bull meteorological stations. Water year 2006 temperatures best reflect the 4-year means. This daily mean is the average of the daily minimum and maximum.

7. Daily precipitation averaged over the four meteorological stations and hourly discharge for water year 2007, a dry water year. Panels for the eight catchments are arranged from highest to lowest mean elevation. Note that ordinate scales are different for the various catchments.

8. Expanded view of daily precipitation averaged over the four meteorological stations and hourly discharge for three 30-day periods, water year 2007. The spring/summer transition in discharge from being snowmelt dominated to evapotranspiration dominated for the eight catchments is illustrated. Catchments are arranged from highest to lowest elevation.

10. Annual discharge and water yield for the eight catchments, as a function of mean catchment elevation.

11. Leaf Area Index (LAI) based on NDVI from LANDSAT (July 7, 2007) for the higher elevation Bull catchments (B201, B203, B204, T003) and the lower elevation Providence catchments (P301, P303, P304, D102). The LAI calculation is based on White et al. (1997). Values should be viewed as relative rather than absolute given the high density of the forest in both Providence and Bull.