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# SNOWMELT RUNOFF AND WATER YIELD ALONG ELEVATION AND TEMPERATURE GRADIENTS IN CALIFORNIA'S SOUTHERN SIERRA NEVADA[1]

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ABSTRACT: Differences in hydrologic response across the rain-snow transition in the southern Sierra Nevada were studied in eight headwater catchments – the Kings River Experimental Watersheds – using continuous precipitation, snowpack, and streamflow measurements. The annual runoff ratio (discharge divided by precipitation) increased about 0.1 per 300 m of mean catchment elevation over the range 1,800-2,400 m. Higher-elevation catchments have lower vegetation density, shallow soils with rapid permeability, and a shorter growing season when compared with those at lower elevations. Average annual temperatures ranged from 6.8°C at 2,400 m to 8.6 at 1,950 m elevation, with annual precipitation being 75-95% snow at the highest elevations *vs.* 20-50% at the lowest. 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. Snowmelt dominated the daily streamflow cycle over a period of about 30 days in higher elevation catchments, followed by a 15-day transition to evapotranspiration dominating the daily streamflow cycle. Discharge from lower elevation catchments was rainfall dominated in spring, with the transition to evapotranspiration dominance being less distinct. Climate warming that results in a longer growing season and a shift from snow to rain would result in earlier runoff and a lower runoff ratio.

(KEY TERMS: forests; snow hydrology; watershed management; runoff ratio; Sierra Nevada; mountain hydrology; headwaters.)

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## 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 the 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.

Water supplies in California and the western United States (U.S.) depend on runoff from mountains, much of which originates as snowmelt in forested

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watersheds. Water is one of the critical ecosystem services provided by forests and grasslands. Because changing climate is expected to dramatically affect the amount and seasonal distribution of rainfall and snowpack, the Forest Service and other land managers have acknowledged the need for new strategies and effective approaches to address these changes (Forest Service, 2008; Salazar, 2009). Forest vegetation management in the Sierra Nevada during the past 20 years has largely focused on the maintenance of dense canopy cover for a few terrestrial species – California spotted owl and Pacific fisher (SNFPA, 2004). The Forest Service's goal of healthy forests is best served by broadening vegetation objectives to address increased soil moisture for plants and water yield for aquatic and human communities.

Numerical simulations suggested that for physiographically heterogeneous basins, such as those 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 relationship 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 the rainfall was above the monthly average. Streamflow changes resulting from regrowth were driven by both interception and transpiration changes. The goals of the research reported here are: (1) to define the differences in hydrologic response across a 600-m elevation range involving a transition from a mixed rain-snow precipitation regime to a snow-dominated regime, using continuous precipitation, temperature, 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 land-management issues for forests; it was established in 2000 (http://www.fs.fed.us/psw/programs/snrc/water/kingsriver).

The catchments range in size from 49 to 228 ha, and have mean elevations ranging from 1,830 to 2,410 m (Table 1). 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). Heights of mature trees are 40-60 m. All watersheds have some meadow except P303. The meadow influence on stream channels varies widely; in B201, 92% of the channel borders meadow whereas 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 Cagwin soils

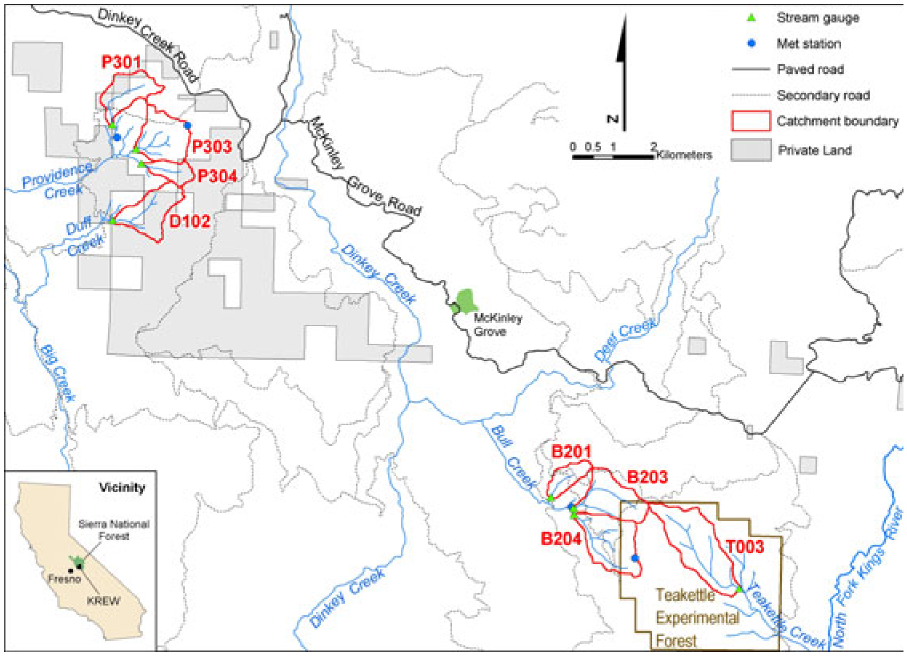


FIGURE 1. Kings River Experimental Watersheds (KREW) Catchments and Instrument Locations. The four Providence catchments in the upper left are at an elevation that receives both rain and snow (P301 99 ha, P303 132 ha, P304 49 ha, and D102 121 ha). The four Bull catchments in the lower right are at an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

TABLE 1. KREW Catchment Characteristics: Area, Elevation, Discharge, and Runoff Ratio.

| Catchment | Area (ha) | Elevation (m) | | | Mean Annual Discharge (mm) | Annual Discharge (mm) | | | | Mean Runoff Ratio |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Outlet | Mean | Top | | 2004 | 2005 | 2006 | 2007 | |
| B203 | 138 | 2,218 | 2,413 | 2,498 | 810 | 379 | 1,298 | 1,328 | 233 | 0.53 |
| B204 | 167 | 2,227 | 2,394 | 2,498 | 708 | 326 | 1,198 | 1,122 | 189 | 0.46 |
| T003 | 228 | 2,062 | 2,309 | 2,498 | 584 | 265 | 819 | 1,009 | 145 | 0.36 |
| B201 | 53 | 2,190 | 2,287 | 2,393 | 544 | 220 | 846 | 919 | 190 | 0.36 |
| P301 | 99 | 1,812 | 2,005 | 2,094 | 528 | 170 | 829 | 1,017 | 99 | 0.32 |
| P303 | 132 | 1,758 | 1,937 | 2,031 | 378 | 118 | 603 | 724 | 70 | 0.23 |
| P304 | 49 | 1,792 | 1,935 | 1,982 | 516 | 259 | 672 | 867 | 267 | 0.36 |
| D102 | 121 | 1,524 | 1,833 | 1,988 | 404 | 132 | 610 | 749 | 123 | 0.26 |

Note: Watersheds are listed from highest elevation (watershed mean) to lowest elevation.

dominate the four higher-elevation catchments (Table 2). 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, Teledyne Isco, Lincoln, NE); electrical-pulse devices (Aquarod™, Advanced Measurements and Controls, Inc., Camano Island, WA) and pressure transducers (Telog™, Telog Instruments, Victor, NY) 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 a 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://www.fsl.orst.edu/climhy.

TABLE 2. KREW Soil Properties by Catchment (Giger and Schmitt, 1993).

| Soil Characteristics | Providence Catchments | | Bull Catchments |
|---|---|---|---|
| Dominant Soil Type | Gerle-Cagwin[1] | Shaver | Cagwin |
| Percent of catchment | P301 is 62% | P303 is 66%<br>P304 is 55%<br>D201 is 48% | B201 is 67%<br>B203 is 80%<br>B204 is 98%<br>T003 is 94% |
| Substratum | 96 cm<br>Highly weathered granodiorite | 185 cm<br>Strongly weathered quartz diorite | 81 cm<br>Highly weathered granitic rock |
| Effective rooting depth | 76 to 127 cm | 102 to 203 cm | 50 to 102 cm |
| Drainage | Well drained | Well drained | Somewhat excessively drained |
| Permeability | Moderately rapid | Moderately rapid | Rapid |
| Available water capacity[2] | Medium | Medium | Low |
| Upper 51 cm (20 in) | 1.6 to 2.0 | 1.9 to 2.2 | 1.1 to 1.4 |
| Total 152 cm (60 in) | 3.0 to 4.6 | 4.2 to 6.2 | 1.1 to 2.5 |
| Hydrologic soil group[3] | B<br>Moderate rate of water transmission | B<br>Moderate rate of water transmission | A<br>High rate of water transmission, low runoff potential |

[1]Gerle-Cagwin soil type is approximately 50% Gerle and 30% Cagwin family (Gerle characteristics given).
[2]The capacity of soils to hold water available for use by most plants expressed as inches per depth. In the upper 51 cm of soil, low <1.2 in, medium 1.2 to 2.4 in, high >2.4 in (capacity value is left in English units of inches).
[3]Rating of soils according to their ability to accept and transmit water down through the profile; uses infiltration, permeability, and depth at which permeability reduction begins.

TABLE 3. KREW Meteorological Characteristics: Temperature, Wind Speed, and Precipitation.

| | | Daily Average (mean ± SD) | | | | WY Total Precipitation (mm) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | WY 2004-2007 Temperature (°C) | | | 2006 Wind Speed[1] (m/s) | | | | |
| Station | Elevation (m) | Min | Mean | Max | | 2004 | 2005 | 2006 | 2007 |
| Lower Providence | 1,730 | 3.4 ± 0.8 | 7.8 ± 1.4 | 15.0 ± 1.2 | 0.68 ± 0.48 | 936 | 1,763 | 2,008 | 760 |
| Upper Providence | 1,950 | 4.5 ± 0.8 | 8.6 ± 0.9 | 13.0 ± 1.0 | 0.83 ± 0.29 | 955 | 1,743 | 2,026 | 770 |
| Lower Bull | 2,160 | 1.3 ± 0.8 | 7.8 ± 1.4 | 13.9 ± 1.3 | 1.02 ± 0.26 | - | 1,783 | 1,926 | 769 |
| Upper Bull | 2,400 | 3.3 ± 1.1 | 6.8 ± 0.8 | 11.2 ± 0.7 | 0.75 ± 0.37 | - | 1,820 | 1,983 | 748 |

Note: WY stands for water year (October 1 through September 30).
[1]WY 2006 is used for illustration as it had the fewest data gaps among the four years.

Four meteorological stations are located at the low and high elevations in both the Providence and Bull sets of catchments (Table 3). 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 and would not be representative of the landscape. Snow pillows (Mendenhall Manufacturing, McClellan, CA) exist at the upper Bull and upper Providence meteorological stations; all four stations have acoustic snow-depth sensors (Judd Communications™ LLC, Salt Lake City, UT) 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 <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™ (Honeywell, Columbus, OH) pressure transducer measures the pressure exerted on the pillow by overlying snow.

Precipitation is collected using Belfort™ 5-780 rain gages (Belfort Instrument, Baltimore, MD) equipped with load cells (Tedea-Huntliegh™ 1042, Tedea-Huntliegh, Canoga Park, CA), mounted 3 m above the ground on large wooden posts. Each gage uses nontoxic, propylene-glycol antifreeze that allows for the 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, NovaLynx Corporation, Grass Valley, CA). Temperature sensors (Vaisala™ HMP45C, Vaisala OYJ, Helsinki, Finland) are in standard enclosures, mounted 4 m above the ground on a 6-m triangular tower. The anemometer for wind measurements (Met One™

013A, Met One Instruments, Grants Pass, OR) is mounted 7 m above the ground. Manual measurements are taken each month as a check on the continuous measurements; instruments are calibrated every two years. Meteorological measurements are logged as 15-min averages (Campbell™ CR10x, Campbell Scientific, Inc., Logan, UT), except for precipitation, which has 1-min averages. Each 15-min average is the mean of 360 samples taken at 2.5-s 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.

Leaf area index (LAI), the ratio of total upper leaf surface of vegetation divided by the surface area of the land on which the vegetation grows, was based on Normalized Difference Vegetation Index (NDVI) from LANDSAT (July 7, 2007). Aggregate values were estimated 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 and saturation issues with LANDSAT at high values.

## RESULTS

For a given year, the 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 2). Precipitation amounts were not corrected for wind influence because daily wind speeds averaged around 1 m/s and were seldom above 2 m/s (Table 3). 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-year) 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 2). 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 3). 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 2). 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 3). 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. Average temperatures for lower Providence (upper Bull) were 7.8 ± 1.4°C (11.3 ± 0.8°C) for the four years, where ± refers to the standard deviation (Table 3). 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 four 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 *vs.* 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 potentially temperature-limited primary productivity in the catchments, that is, 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 4). 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 in Figure 5, for example, days 170, 177, and 215.

The same proportion of annual runoff occurred about 30 to 45 days earlier in the lowest elevation catchment when compared with the highest elevation catchment in both wet and dry years (Figure 6), reflecting the greater proportion of rainfall at lower elevations. In lower elevation D102, half of the annual discharge occurred by water-year day 160 (March 8) in the drier years 2004 and 2007, *vs.* water-year day 189 (April 6) for higher-elevation

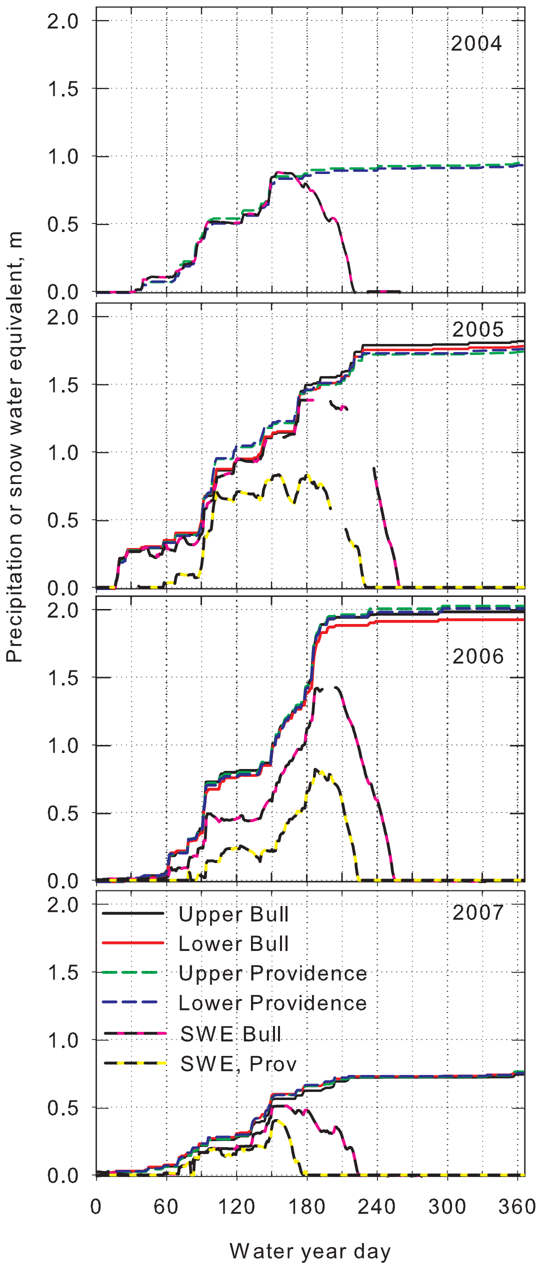


FIGURE 2. Cumulative Precipitation Amounts for the Four Meteorological Stations and Snow Water Equivalent (SWE) for Upper Bull and Upper Providence Stations. The upper Providence snow pillow and the Bull meteorological stations were not active in water year 2004.

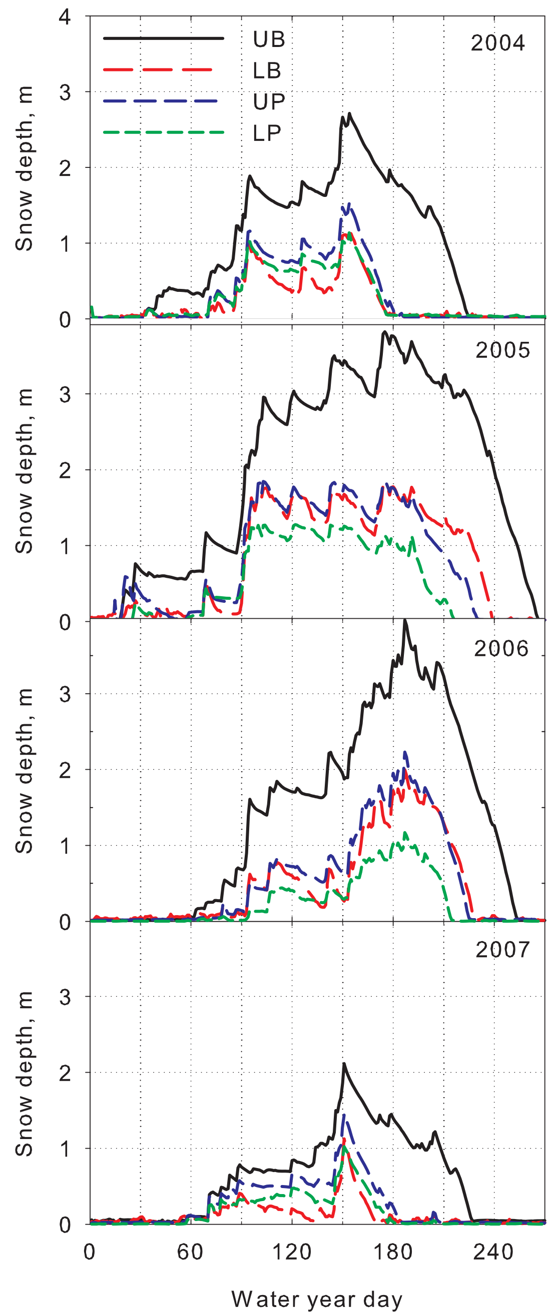


FIGURE 3. Snow Depths at the Four Meteorological Stations from 2004 Through 2007. Station codes: UB = upper Bull, LB = lower Bull, UP = upper Providence, and LP = lower Providence.

B203 in the same years. In the wetter years, the corresponding days for D102 and B203 were 187 (April 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 daily patterns and a later period dominated by evapotranspiration (Figure 5). This transition occurs when the daily discharge starts to level off and the night and day fluctuation increases substantially. 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.

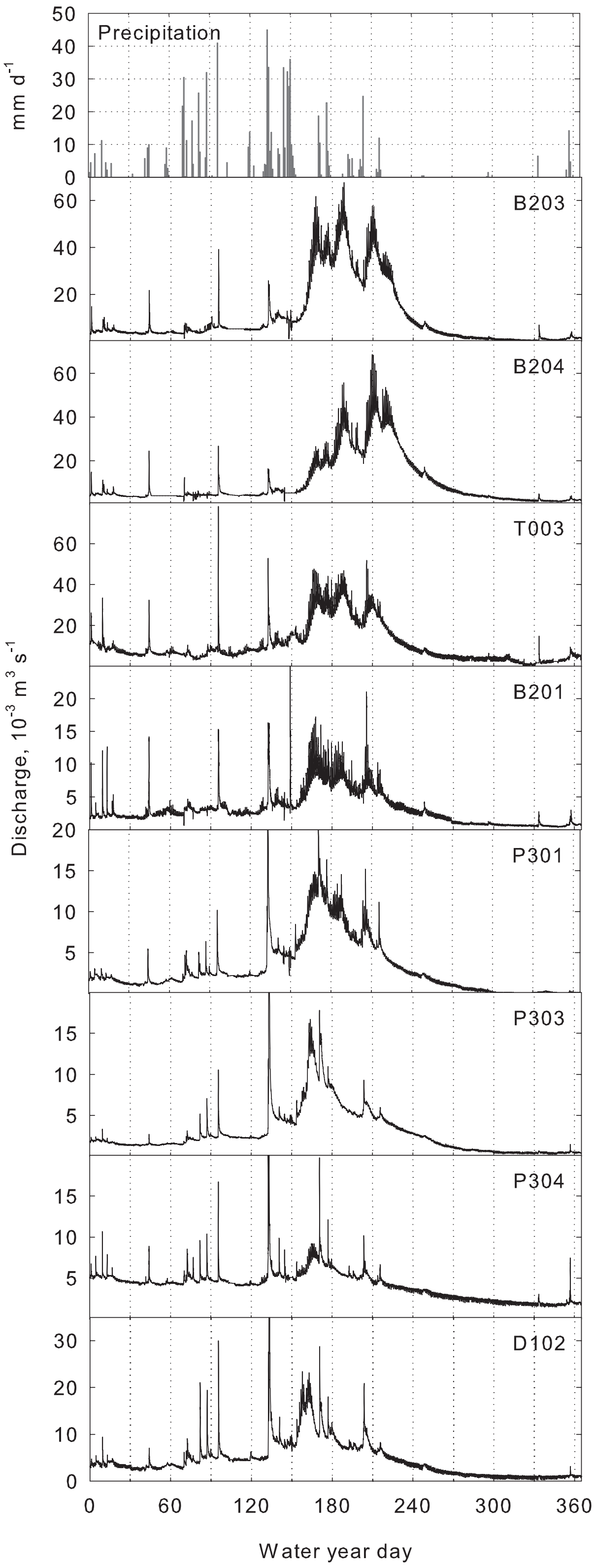


FIGURE 4. Daily Precipitation Averaged Over the Four Meteorological Stations and Hourly Discharge for Water Year 2007, a Drier Water Year. Panels for the eight catchments are arranged from highest to lowest mean elevation. Note that ordinate scales are different for the various catchments.

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 daily cycles in streamflow, the lag between peak temperature and peak discharge was 3 to 6 h. For the post-snowmelt period when evapotranspiration dominated daily cycles in streamflow, the lag between peak temperature and peak discharge was 17 to 19 h, and the lag between peak temperature and minimum discharge was 3 to 6 h. Lags in the four 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 7). 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. Dividing discharge by precipitation shows that, for the four years, water yield as a fraction of precipitation (runoff ratio) increases by 0.10, 0.16, 0.10, and 0.05, 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 *vs.* mixed rain and snow catchments. The 30- to 60-day earlier transition to evapotransition (Figure 5) 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 run-

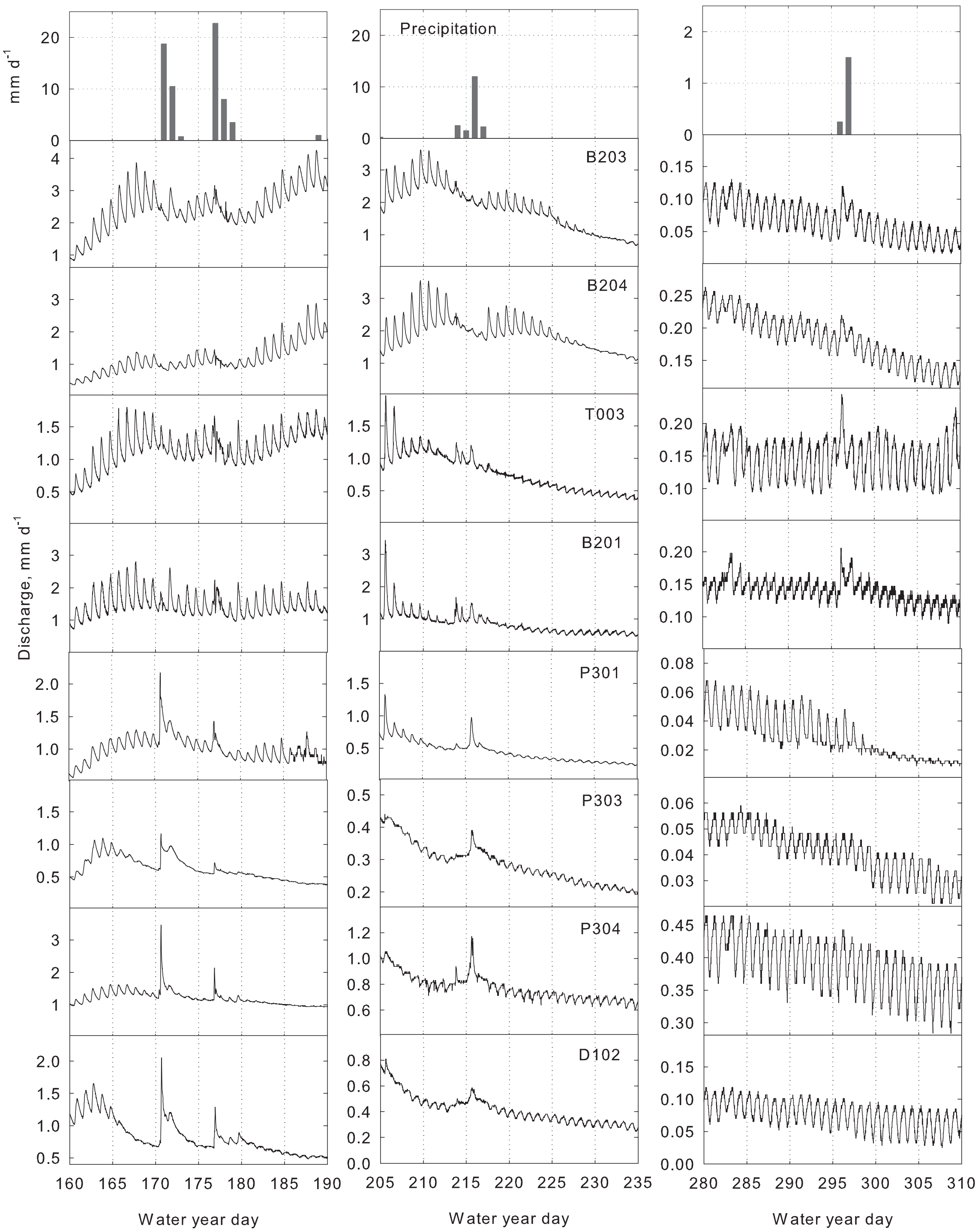


FIGURE 5. Expanded View of Daily Precipitation Averaged Over the Four Meteorological Stations and Hourly Discharge for Three 30-Day Periods, Water Year 2007. The spring/summer transition in discharge from being snowmelt-dominated (Panel 1, days 160 to 190 and Panel 2, days 205 to 235 or May) to evapotranspiration-dominated (Panel 3, after day 280 or June) for the eight catchments is illustrated. Catchments are arranged from highest to lowest elevation.

off ratio and thus water yield increase significantly with elevation (Table 1). Dividing discharge by precipitation shows the runoff ratios to be about 0.10 to 0.35 in drier years and 0.35 to 0.70 in wetter years (Figure 7). 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 four years of record (Table 3). Armstrong and Stidd (1967) show that precipitation on the west side of the Sierra

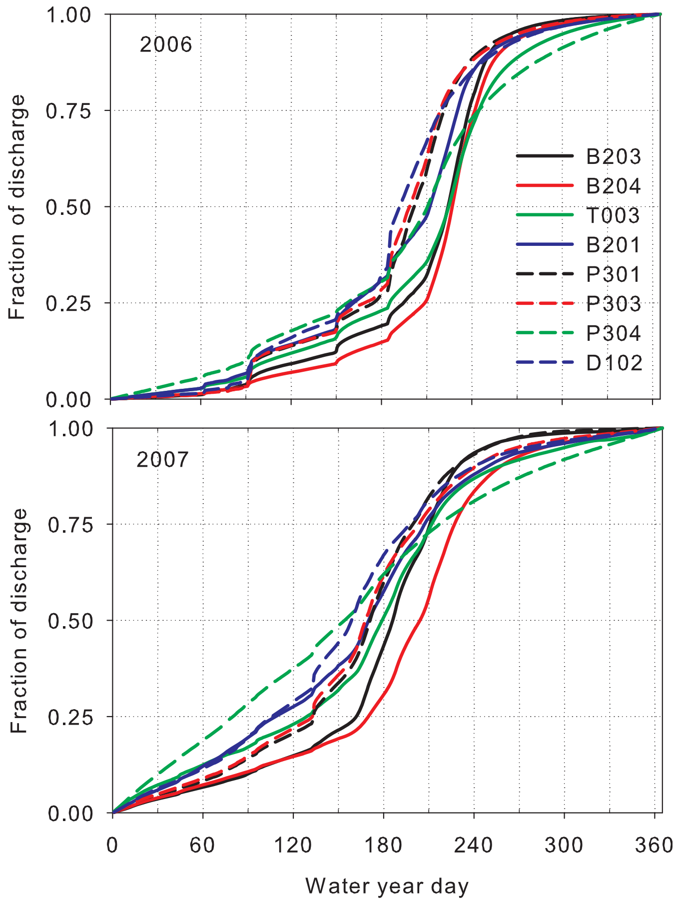


FIGURE 6. Cumulative Water-Year Discharge in Wet (2006) and Dry (2007) Years.

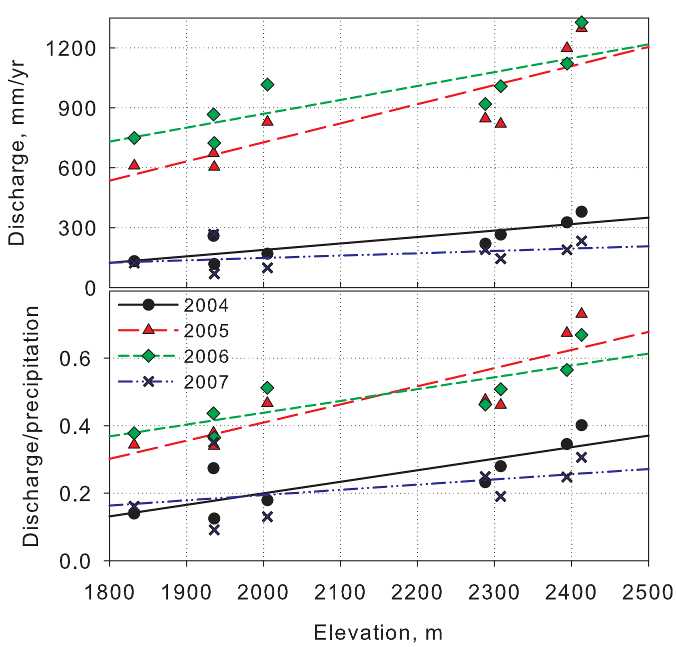


FIGURE 7. Annual Discharge and Water Yield for the Eight Catchments, as a Function of Mean Catchment Elevation.

Nevada (American River Basin) reaches a maximum at about 1,200 m (50 years of data for 65 gages), thus supporting the observation of similar precipitation at the elevations of the Providence and Bull catchments. 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, that is, annual runoff increases with precipitation and decreases with a higher fraction of forest cover (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 four years analyzed, are in the same range as the 60 mm/year average reported by Dingman (1981) for 49 New England catchments. Armstrong and Stidd (1967) estimate the components of the moisture balance (interception, evapotranspiration, runoff) for an elevation gradient in the American River Basin. Runoff continuously increases whereas interception and evapotranspiration maximize at about 1,500 m. At 1,200 m, they suggest runoff and evapotranspiration are about equal at 40% of total (interception 20%) whereas at 2,100 m runoff increases to 68% of the total. 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. Part of the observed difference in soils and vegetation with elevation is a long-term product of small climatic gradients, resulting in soil formation, and vegetation response in temperature-limited regimes. Extensive soils data have been collected at KREW (Johnson *et al.*, 2011). Elevation has a significant (but poor) negative correlation to phosphorus soil content, but no significant correlations were found for rock content, bulk density, carbon, or nitrogen. Although there are large differences in the general description of the Shaver and Cagwin soils (Table 2), there were no statistically significant differences in soil-rock content, depth, bulk density, or nutrient contents for the 1-m deep soil pits.

LAI for the Bull catchments is about 60% of that at the lower elevations (2.0 ± 1.0 *vs.* 3.1 ± 1.0). Multiple factors contribute to this difference. The Providence catchments have more understory vegetation, for example, 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). Together, these highlight the potential for active vegetation management to influence water yield.

The difference in runoff ratio between the lower *vs.* upper catchments was 0.10 in dry and 0.17 in wet years (Figure 7) with the largest difference in mean values (0.30, Table 1), where LAI at the upper catchments is 56% of that at the lower catchments. Using the analysis of Zhang *et al.* (2001), a comparable difference in forest cover gives differences of 0.06 and 0.08 in dry and wet years, respectively (same precipitation as Zhang *et al.* and $w = 0.5$). Note that the higher observed differences result from the combined effects of vegetation, soils, and temperature.

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 the 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, that is, 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 *vs.* dry years.

Although there is ample evidence that reductions in LAI, for example, 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. Because these catchments have sufficient subsurface water storage so that photosynthesis by trees is apparently not water limited in summer and fall (Bales *et al.*, 2011), the removal of vegetation should reduce annual evapotranspiration. Although a recent review of past watershed studies cautions managers about thinking that timber harvest is the way to provide significant, sustained increases in water yield (National Research Council, 2008), contemporary strategies for vegetation management can provide more sustained changes in water yields through understory management, improve forest health, and reduce wildfire risk. Downstream water uses clearly benefit from these actions.

KREW was established as a paired-watershed study (with controls) to evaluate effects from vegetation management to create a more sustainable forest. Differences from mechanical thinning, underburning, and the combination of thinning and underburning will be evaluated. Catchment T003 provides a unique control as this catchment has no influence of roads or timber harvest.

## CONCLUSIONS

Small temperature differences between rain- *vs.* snow-dominated catchments result in significantly different timing of runoff and runoff ratios in Sierra Nevada mixed-conifer catchments. The approximately 600-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. Given the potential economic implications of this timing, the potential for vegetation management to influence this timing warrants attention.

A longer growing season and more vegetation in the mixed rain-snow-dominated *vs.* higher-elevation snow-dominated catchments result in more evapotranspiration and canopy interception and thus lower water yield at the lower elevations. Both climate warming and forest management have the potential to significantly alter future hydrologic response of Sierra Nevada-forested catchments. Considering a 2°C average temperature increase to represent conditions 300-400 m lower in elevation, climate warming by 2°C could result in a decrease in annual runoff ratio of as much as 0.1. Findings at these southern Sierra Nevada catchments also suggest that gains in water yield through LAI changes can occur in both the mixed rain-snow- and snow-dominated forests, although objectives at the snow-dominated elevations should include strategies to attenuate snowmelt as well as reduce evapotranspiration. Data from the collaboration of KREW and the Southern Sierra Critical Zone Observatory (Bales *et al.*, 2011) should allow a complete picture of water balance, across an elevation gradient, through the seasons for the mixed-conifer forests of the southern Sierra including evapotranspiration, runoff, growing season length, phenology, summer/winter plant shut down periods, etc.

The pairing of a set of rain and snow catchments with a set of snow-dominated catchments at KREW may provide unique insights for the transitional elevation band during coming decades, and can contribute toward predicting climate change effects on mountainous forest ecosystems. KREW has established an excellent baseline for these catchments so that once the forest vegetation treatments are performed, any changes in water yield can also be evaluated with respect to vegetation change, current precipitation regime, and expected conditions with climate change.

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