Snowmelt Discharge Characteristics Sierra Nevada, California

By David Peterson, Richard Smith, Iris Stewart, Noah Knowles, Chris Soulard,
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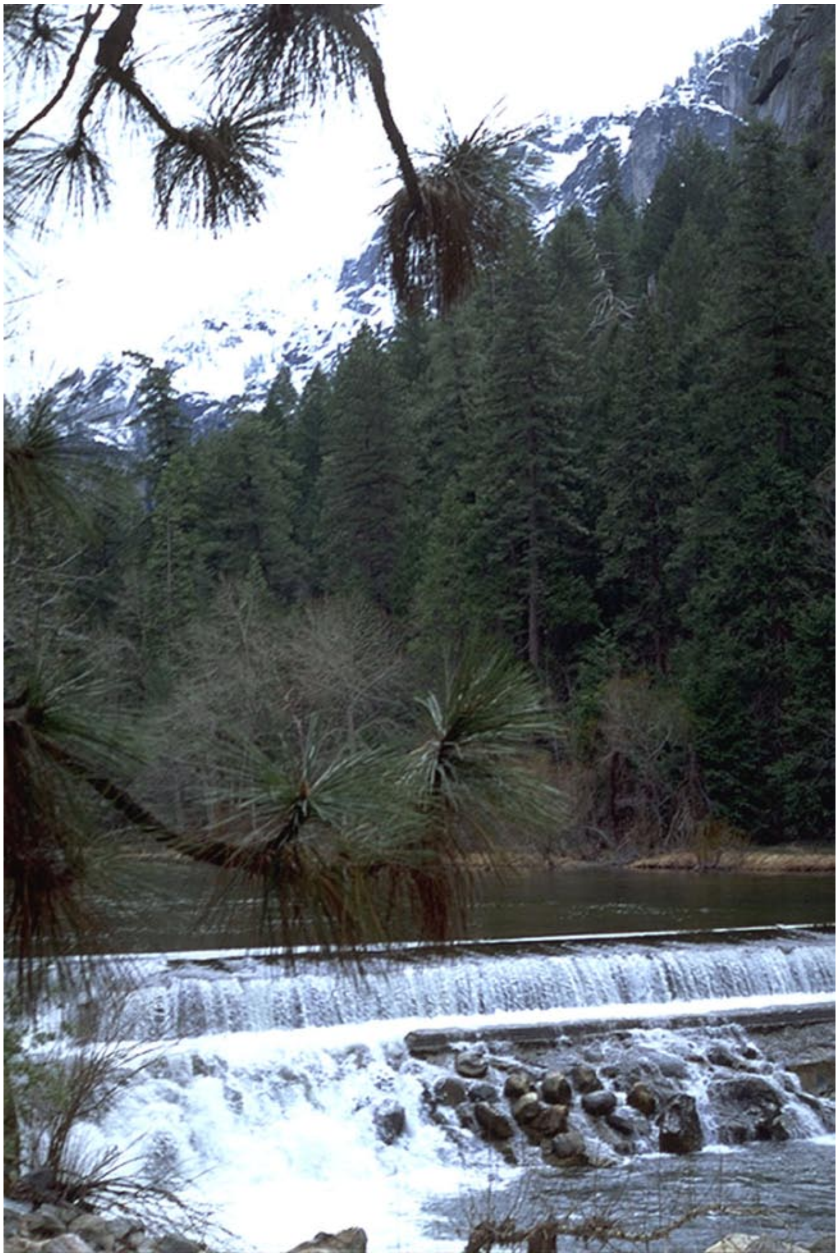

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ABSTRACT

Alpine snow is an important water resource in California and the western U.S. Three major features of alpine snowmelt are the spring pulse (the first surge in snowmelt-driven river discharge in spring), maximum snowmelt discharge, and base flow (low river discharge supported by groundwater in fall). A long term data set of hydrologic measurements at 24 gage locations in 20 watersheds in the Sierra Nevada was investigated to relate patterns of snowmelt with stream discharge In wet years, the daily variations in snowmelt discharge at all the gage locations in the Sierra Nevada correlate strongly with the centrally located Merced River at Happy Isles, Yosemite National Park (i.e., in 1983, the mean of the 23 correlations was R= 0.93 + 0.09) ; in dry years, however, this correlation breaks down (i.e., in year 1977, R=0.72 + 0.24). A general trend towards earlier snowmelt was found and modeled using correlations with the timing of the spring pulse and the river discharge center of mass. For the 24 river and creek gage locations in this study, the spring pulse appeared to be a more sensitive measure of early snowmelt than the center of mass. The amplitude of maximum daily snowmelt discharge correlates strongly with initial snow water equivalent. Geologic factors, base rock permeability and soil-to-bedrock ratio, influence snowmelt flow pathways. Although both surface and ground water flows and water levels increase in wet years compared to dry years, the increase was greater for surface water in a watershed with relatively impermeable base rock than for surface water in a watershed with highly permeable base rock The relation was the opposite for base flow (ground water). The increase was greater for groundwater in a watershed with permeable rock compared to ground water in a watershed with impermeable rock. A similar, but weaker, surface/groundwater partitioning was observed in relatively impermeable granitic watersheds with differing soil-to-bedrock ratios. The increase in surface flow was greater in a watershed with a low, compared to a high, soil-to-bedrock ratio; whereas the increase in ground water flow was greater in a watershed with a high, compared to a low, soil-to-bedrock ratio. Transects that include long-term observations of shallow well-water depth and chemistry would complement traditional hydroclimate data and provide a more complete understanding of hydrologic controls of snowmelt.

INTRODUCTION

Climate is the major source of variability in our nation's and global water resources. For example, large-scale variations in the ocean and atmosphere are linked to variations in river discharge in Hawaii, Alaska, the Pacific Northwest and Southwest (Cayan and Peterson, 1989). Similar phenomena are linked to variations in major water and energy resources of Western U.S. (Cayan, et al, 2005). Spring air temperatures are increasing across much of North America causing snowmelt-driven river discharge and plant blooming to start earlier in the year (Cayan, et al., 2001, Stewart, et. al.,2004 and in press). Additionally, an atmospheric warming trend is causing river discharge to be less snowmelt-driven relative to rain at intermediate elevations across California (Roos, 1987) and the western U.S. (Dettinger and Cayan, 1995). If this loss of snow continues, reservoir management to control floods and supply water will be more difficult, because snow pack provides a natural reservoir (more water storage capacity) by storing precipitation for several months and snow pack is a more reliable water resource than rain.

A large scale study of western US snowmelt-driven river discharge was proposed because many alpine linkages, processes, and responses are of similarly large scale. Also, high elevation watersheds have fewer human influences than low elevation watersheds. This initial effort was limited to the Sierra Nevada, California. Major topics are: the spring pulse (the first surge in snowmelt discharge, Cayan et. al., 1999), maximum discharge, and base flow characteristics of snowmelt discharge (SMD). Eighteen of the approximately one hundred alpine snowmelt-driven western U.S. watersheds were studied.

The following report gives data sources and methods, a brief introduction to California hydroclimatology, results of estimating the trend towards earlier snowmelt in the Sierra Nevada, preliminary results in developing the statistics to forecast maximum daily snowmelt discharge (MDSMD), implications of base flow characteristics, and future research plans and needs.

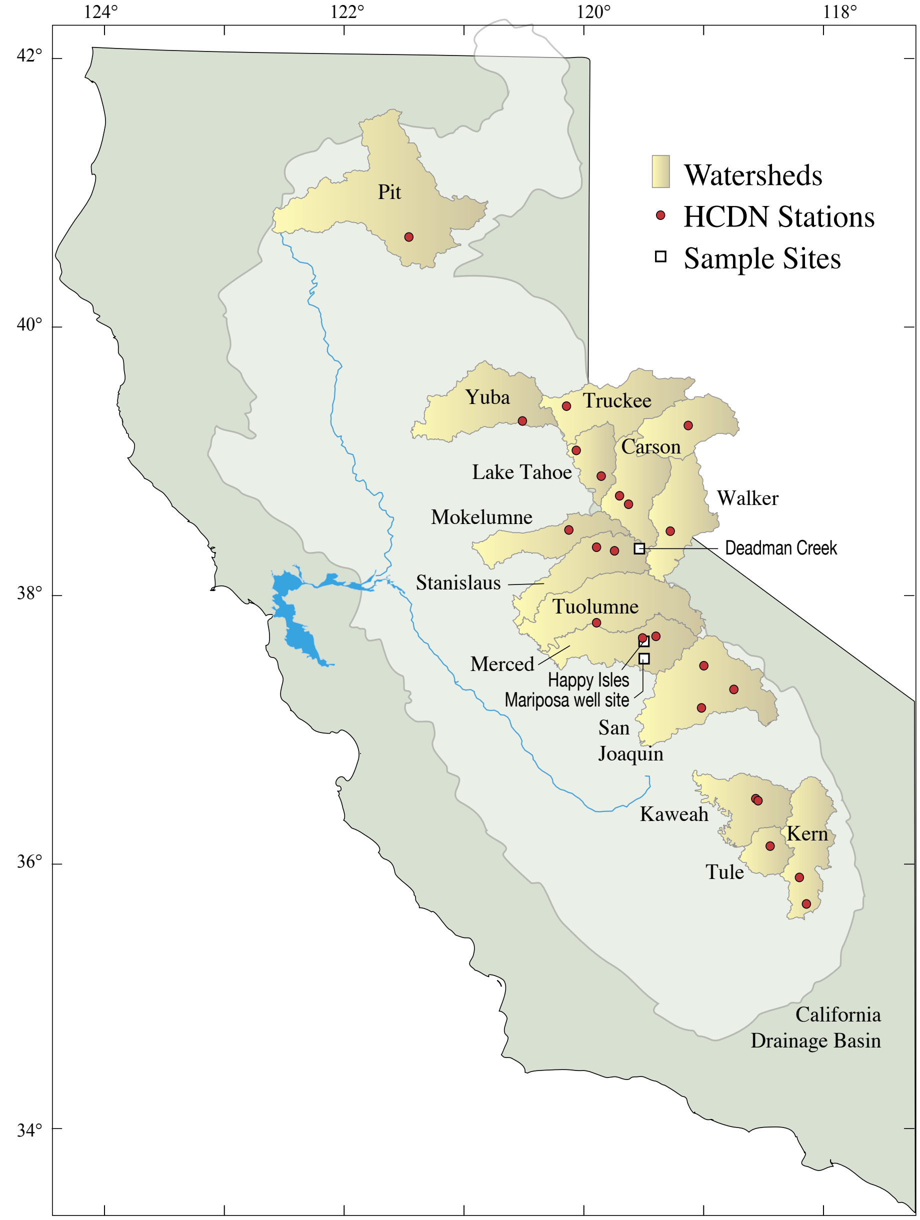


Figure 1. Map of watershed area and river discharge gage locations in the Sierra Nevada, California.

PURPOSE AND SCOPE

This study contributes towards a broad-scale understanding of alpine snowmelt discharge characteristics. Snow is a reliable water resource in the western U.S., and in other mountainous parts of the world. Thus, snowmelt discharge variability is an important water management issue. Further, the nature of snowmelt discharge variability, such as magnitude and timing, is also a critical area of scientific research in hydroclimate variability and change.

This study is largely based on observations of snowpack and snowmelt discharge in the Sierra Nevada, by the California Department of Water Resources and the USGS, including analysis for trends in the spring pulse timing in snowmelt discharge, prediction of the magnitude of the annual snowmelt discharge maximum, and geologic- and climate- caused variations in river and stream base flow.

DATA AND METHODS

River discharge is from the USGS Hydroclimatic Data Network (HCDN, Slack and Landwehr 1992). The selection criteria for snowmelt driven watersheds is described in Stewart, Cayan, and Dettinger (2004). Matching river discharge (HCDN) and snow pack observations (Appendix C, Fig 1C) are from California snow course and sensor data, Climate Data Exchange Center (CDEC). The watershed boundaries and the locations of the river discharge gages are in Fig.1., watershed statistics are in Table 1.

The trend towards earlier timing of snowmelt was modeled by using the historical changes in timing of the spring pulse (Cayan et. al.,1999; Cayan et. al., 2001; and Stewart, et. al., 2004, and in press) and the center of mass of river discharge (Cayan, et. al., 2001; Stewart, et. al., 2004, and in press). These references include the details on the statistical methods to estimate early timing. Statistical parameters of the linear regression between initial snow pack and MDSMD were estimated by standard methods (Peterson, et. al., 2002). Visual inspection of the SMD decline allowed comparisons among the annual time series and estimation of the differences in base flow among years. The data for these comparisons generally fell between August 13 and October 2nd. This subjective procedure was use to minimize the errors caused by Fall season rain events that "reset" the discharge as discharge declines towards base flow.

Table 1 List of watersheds and associated USGS gages used in this study.

[Elevations are given in meters above NGVD29. Area is watershed area above gage. Years represent the length of record for the gage.]

Station Name	USGS Gage No.	Gage Elevation (meters)	Area (km^2)	Years
Kern at Kernville	11187000	846	2,613	1912 - present
Combined Kern	11186001	799.1	2,191	1961 - present
North Fork Tule	11202001	2,920	101.8	1940 - present
Middle Fork Kaweah	11206501	2,100	264.2	1949 - present
Marble Fork Kaweah	11208011	2,150	133.1	1950 - present
Pitman Creek	11237500	2,140	59.3	1927 - present
Bear Creek	11230500	2,245	136	1948 - present
San Joaquin at Millers Crossing1	11226500	1,392	644.9	1951 - 1991
Merced at Happy Isles	11264500	1,224	468.8	1915 - present
Merced at Pohono	11266500	1,177	831.4	1916 - present
Middle Fork Tuolumne	11282000	853	190.4	1916 - present
Stanislous at Clark Fork1	11292500	1,679	174.8	1950 - 1994
Highland Creek2	11294000	1,932	119.1	1952 - present
West Walker	10296000	2,009	468.9	1938 - present
West Walker near Colville	10296500	1,683	640.1	1957 - present
Cole Creek	11315000	1,804	54.4	1943 - present
East Fork Carson	10308200	1,646	714.8	1960 - present
West Fork Carson	10310000	1,754	169.4	1938 - present
Trout Creek	10336780	1,902	95.1	1960 - present
Blackwood Creek	10336660	1,900	29.0	1960 - present
Carson near Fort Churchill	10312000	1,285	3,372	1911 - present
South Yuba1	11414000	1,683	134.2	1942 -1994
Sagehen Creek	10343500	1,926	27.2	1953 - present
Hat Creek1	11355500	1,311	419.6	1930 - 1994

1/ Discontinued.

2/ Record altered 1989 to present.

RESULTS AND DISCUSSION

Climate

California climate and water are described in The California Water Atlas (Kahrl, 1978). California has a Mediterranean climate with wet winters and dry summers. Mountain air temperature decreases with increasing elevation and, as a result, precipitation is rain at low elevations, snow at high elevations, and a mix of rain and snow at intermediate elevations. In general, the Sierra Nevada elevation decreases and precipitation increases from south to north. Atmospheric transport of water vapor is from west to east. Thus, the east side of the mountain range is dryer than the west side, due to the "rain shadow".

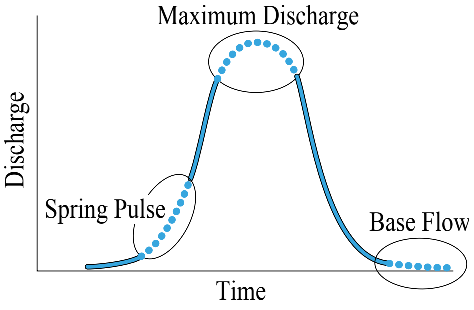
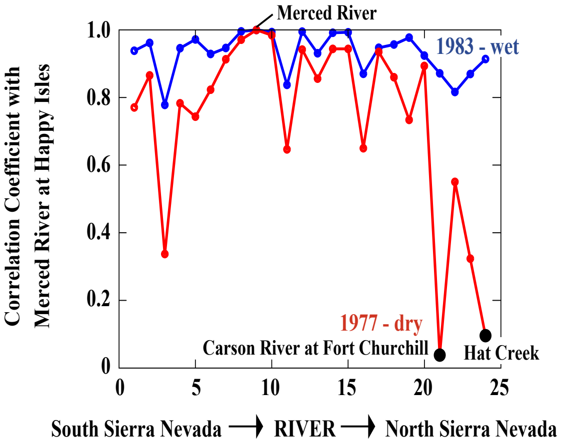


Figure 2. Schematic illustration of three major features of the snowmelt discharge hydrograph.



Three major features of the annual Sierra Nevada snowmelt discharge cycle are the spring pulse, maximum discharge (including maximum daily snowmelt discharge), and base flow (Fig. 2). The spring pulse timing is influenced more by air temperature than size of the initial snow pack (snow depth or snow water equivalent, SWE, on or near April 1). The spring pulse is the first large response to an increase in temperature that ripens the snow pack and then triggers the surge in snowmelt discharge. The maximum daily snowmelt discharge (MDSMD) is influenced more by initial SWE size than air temperature value (Peterson, et al., 2004). A large initial SWE is more likely to result in high (and delayed) MDSMD than a small initial SWE (it takes more time to melt more snow). Base flow is sustained by, and a measure of, ground water. The timing of the spring pulse is mid-April, MDSMD is in late May, early June, and base flow is in late Fall.

Air Temperature and River Discharge

Variations in SMD strongly correlate with variations in air temperature. Because alpine temperature variations are large scale, SMD variations are large scale, cutting across many watersheds (Peterson, et. al., 2000). The correlations are strong in wet winters when snow pack is widespread (Fig. 3

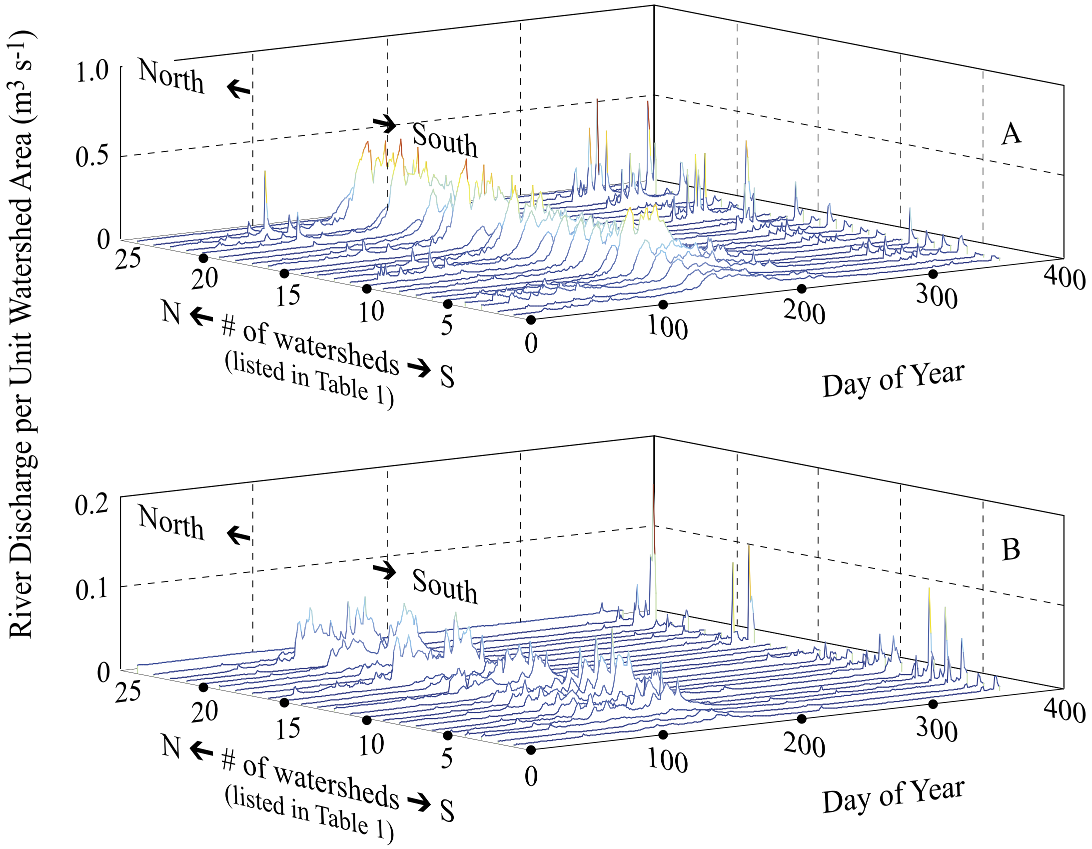


Figure 4. Daily south to north Sierra Nevada snowmelt river discharge in a wet year, 1983, panel A, and in a dry year, 1977, panel B. Note the south to north increase in discharge (normalized to the watershed area above the river discharge gage) and the almost order-of-magnitude difference in daily discharge between wet and dry snowmelt discharge.

and Fig. 4, panel A), and weakens in dry winters, when snow pack is not widespread. Note that two watersheds are uncorrelated in the dry year. Hat Creek is underlain with volcanic rock which has a high rate of snowmelt infiltration, creating the appearance of low-pass filtered SMD (Tague and Grant, 2004), and this influence on flow characteristics is greater in a dry than wet year. The Carson River at Fort Churchill, is influenced by upstream agricultural diversion and the apparent influence on flow characteristics is also greater in a dry than wet year (for other examples causing the decreasing correlation in dry years, see Peterson et. al., 2000).

Spring Pulse

The progression towards earlier snowmelt across North America (Cayan, et. al., 2001), has been illustrated by the historical timing of the spring pulse and the river discharge center of mass (Stewart, et. al., 2004, and in press). In the Sierra

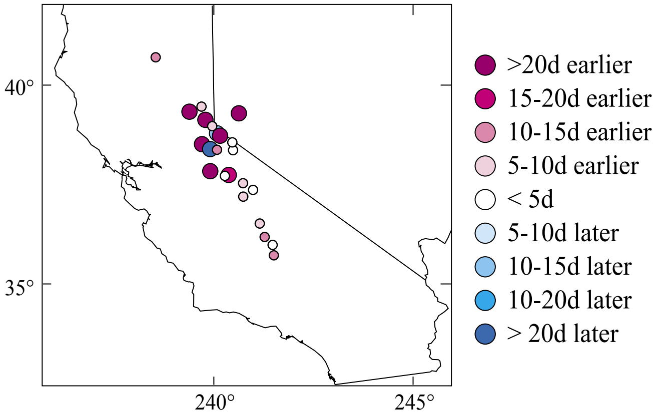


Figure 5. Trends (1948-2002) in snowmelt discharge timing, based on the spring pulse. For example, a 15-20 day earlier trend means the linear trend estimate in the timing of the spring pulse starting in 1948 was 15-20 days earlier in 2002. Large circles are trends that are significant at the 95% confidence level; small circles are not statistically significant.

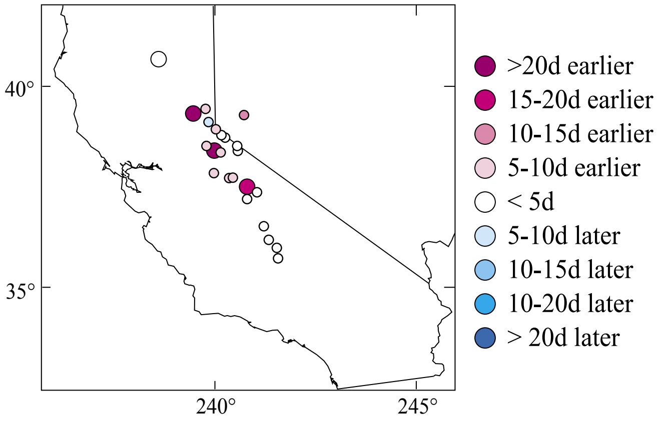


Figure 6. Trends (1948-2002) in snowmelt discharge timing, based on the center of mass, with the same timing interpretation as in Fig. 4. Large circles are trends that are significant at the 95% confidence level; small circles are not statistically significant.

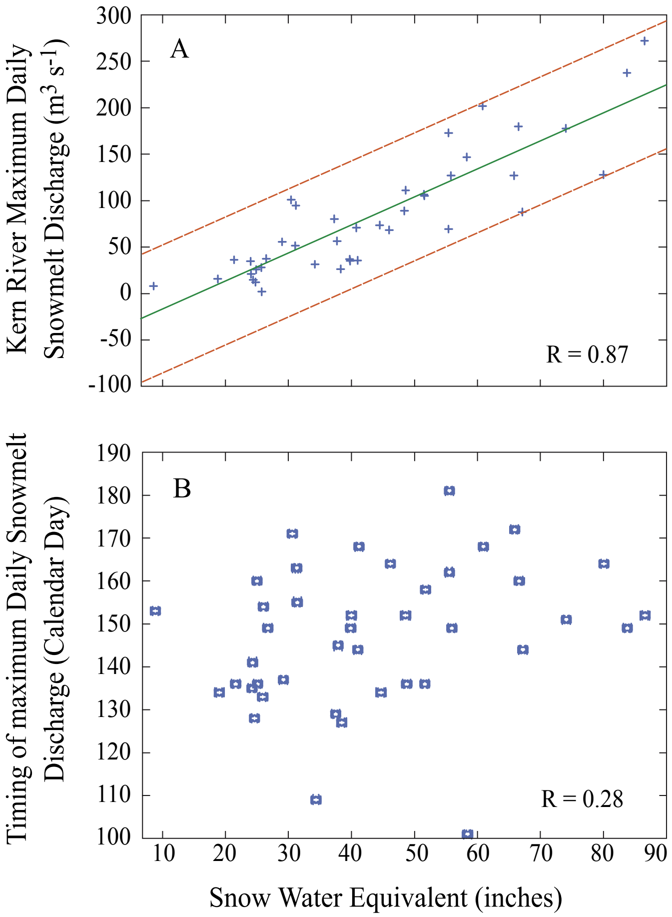


Figure 7 A) correlation in the amplitude of maximum daily snowmelt discharge with initial snow water equivalent, Kern River: B) correlation in day of the year of maximum daily snowmelt discharge with initial snow water equivalent, Kern river.

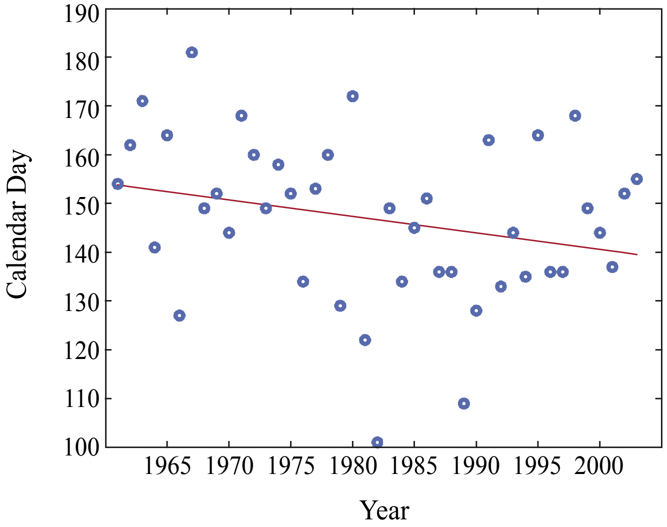


Figure 8. Trend in the timing of snowmelt discharge based on the day of maximum daily discharge, Kern River.

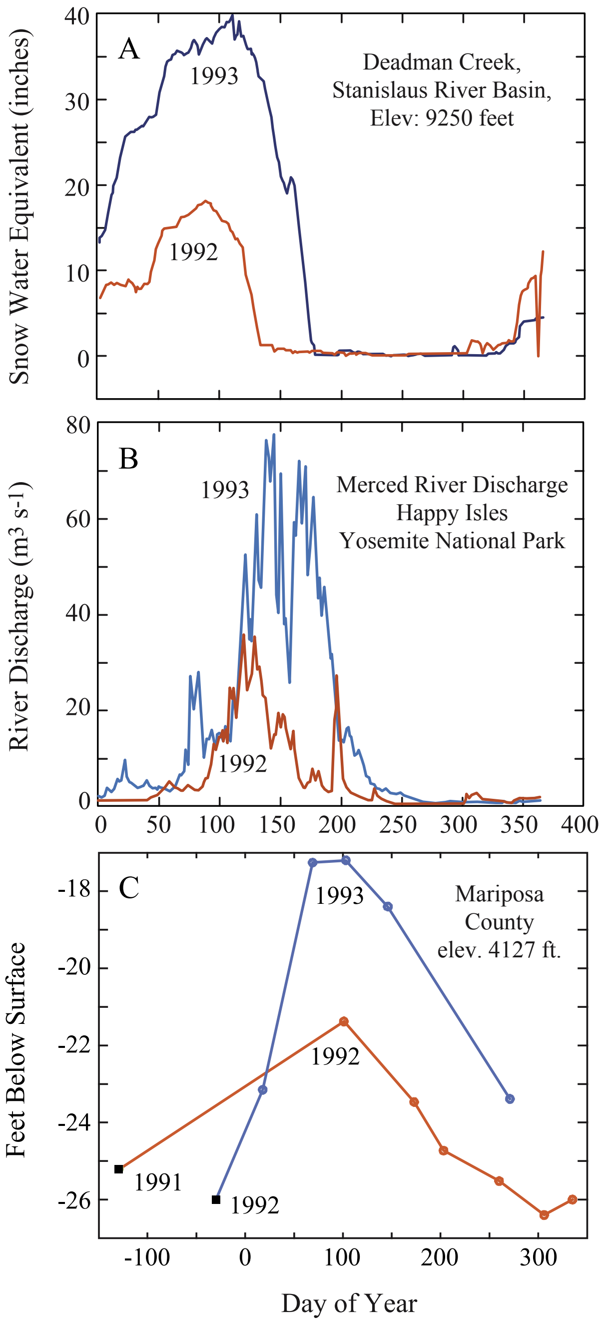


Figure 9. Comparison of snow pack (A), river discharge (B), and well water depth (C), in wet (blue) and dry (red) years. Well data (C) from USGS site number 373256119383001.

Nevada, the spring pulse is a more sensitive detector of early snowmelt than the center of mass, as illustrated by statistically stronger and spatially more extensive early melt pattern from the spring pulse estimates, than from the center of mass estimates (Figs. 5 and 6). The center of mass timing is water year based (starts on Oct. 1 of the previous year) and indicates climate over a period of several months; whereas the spring pulse timing, reflects the air temperature around the time of snowmelt only.

The individual watershed results for the spring pulse and center of mass methods are in Appendix B. The mean in timing is earlier and the deviations from the mean are larger at low elevations.

Maximum Discharge

The amplitude of MDSMD correlates strongly, the timing correlation is weak, but varies among watersheds (Figs. 7 and 8). This linear correlation between MDSMD amplitude and initial SWE can be used to predict MDSMD weeks in advance because the initial SWE observation is made near April 1, whereas MDSMD typically occurs two months later, in early June (Peterson, et al., 2002; examples and trend statistics are in Appendix C).

Note, the long term trend in timing of MDSMD appears to be another, but probably less sensitive, measure of early snowmelt. (Fig. 9; see also Peterson et. al., 2004).

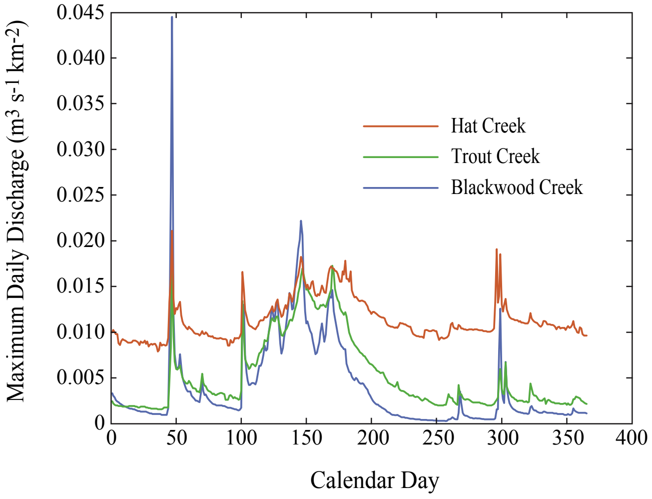


Figure 10. Long term mean of runoff for Creeks with differing rock composition: Hat Creek, permeable volcanic (red); Trout Creek, permeable unconsolidated sediments (green); and Blackwood Creek, impermeable Pliocene volcanic rock (blue). Note, besides the differences in base flow, the peak flow persists longer in the permeable vs. impermeable based watershed.

Base Flow

SMD and associated weather variables have been monitored in some alpine watersheds for almost a century. Thus, hydroclimatology has focused primarily on the connection between climate and surface water. To the best of our knowledge, long-term observations of snowmelt-driven variations in shallow groundwater (Fig. 10) have not been made. Nevertheless, observations of base flow, the low river discharge in fall, provide insight into the process of snowmelt partitioning between surface and ground water in watersheds of differing rock types and soil cover.

In wet years, both surface river flows and ground water levels increase. These increases are influenced by geology. Watersheds with porous and permeable rock, have a relatively low maximum surface flow, and a relatively high base flow, compared to watersheds with relatively impermeable granite. For example, in some volcanic rock watersheds, the high flow snowmelt discharge peaks are muted compared to granitic watersheds (Tague and Grant, 2004). More subtle is the persistence in peak SMD in permeable as compared to relatively impermeable granite watersheds (Fig. 10).

To illustrate the strong influence of permeable rock on SMD (Tague and Grant, 2004), an unconsolidated sediment based watershed (Trout Creek) was compared to a consolidated relatively impermeable Pliocene volcanic rock watershed (Blackwood Creek). The mean annual surface water variations, based on the yearly SMD in impermeable (Blackwood Creek) and in permeable (Trout Creek) basins are correlated (Fig. 11, A and B). In addition, the differences in impermeable mean annual SMD and permeable annual SMD, increase as a function of increasing mean annual SMD (Fig. 11, C) or SWE. However, the ground water (base flow) response shows the opposite relation. The difference between the impermeable base flow and the permeable base flow decreases as a function of increasing mean annual SMD (Fig. 11, D). Note this latter difference is based on a subjective eyeball estimate.

This reversal in response between surface and ground water is also apparent when comparing more subtle differences, such as granite-based watersheds with different soil to bedrock ratios. For example, in the watershed above Happy Isles, Merced River, Yosemite National Park, much of the soil and talus was removed during the most recent glaciation, which ended 10,000 years ago. Thus, the watershed above Happy Isles, Yosemite National Park has a lower soil to bedrock ratio than the West Walker River. The lower soil to bedrock ratio is indicated by the lower base flow at Happy Isles compared to the West Walker (Fig. 12, A) and by the

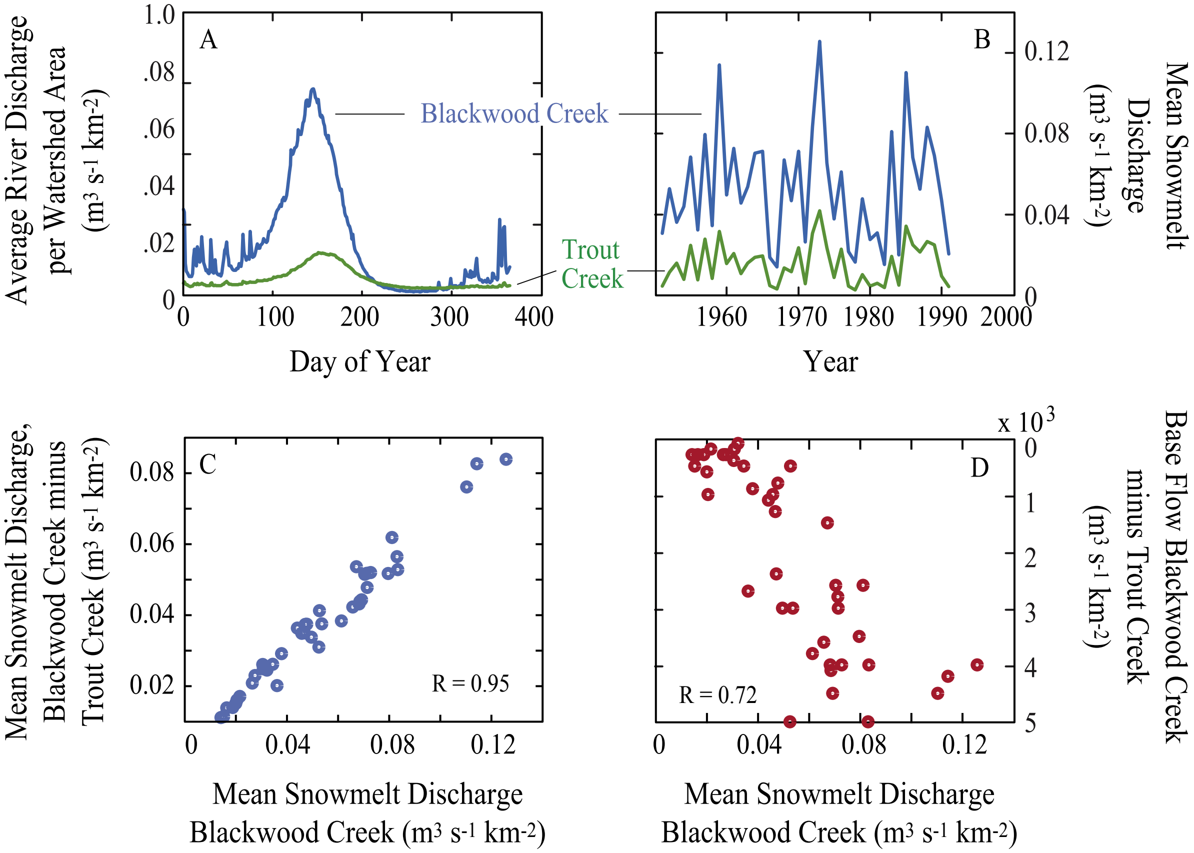


Figure12. A) Long term mean discharge, Blackwood Creek (blue) and Trout Creek (green); B) Blackwood Creek (blue) and Trout Creek (green) mean annual snowmelt river discharge (averaged over days 105-275 to minimize rain contamination) , 1961-2001; C) Blackwood Creek minus Trout Creek mean annual snowmelt river discharge plotted against Blackwood Creek mean annual snowmelt river discharge; D) Blackwood Creek minus Trout Creek annual base (low) flow, plotted against Blackwood Creek mean annual snowmelt river discharge. Note the reversal in C and D correlations.

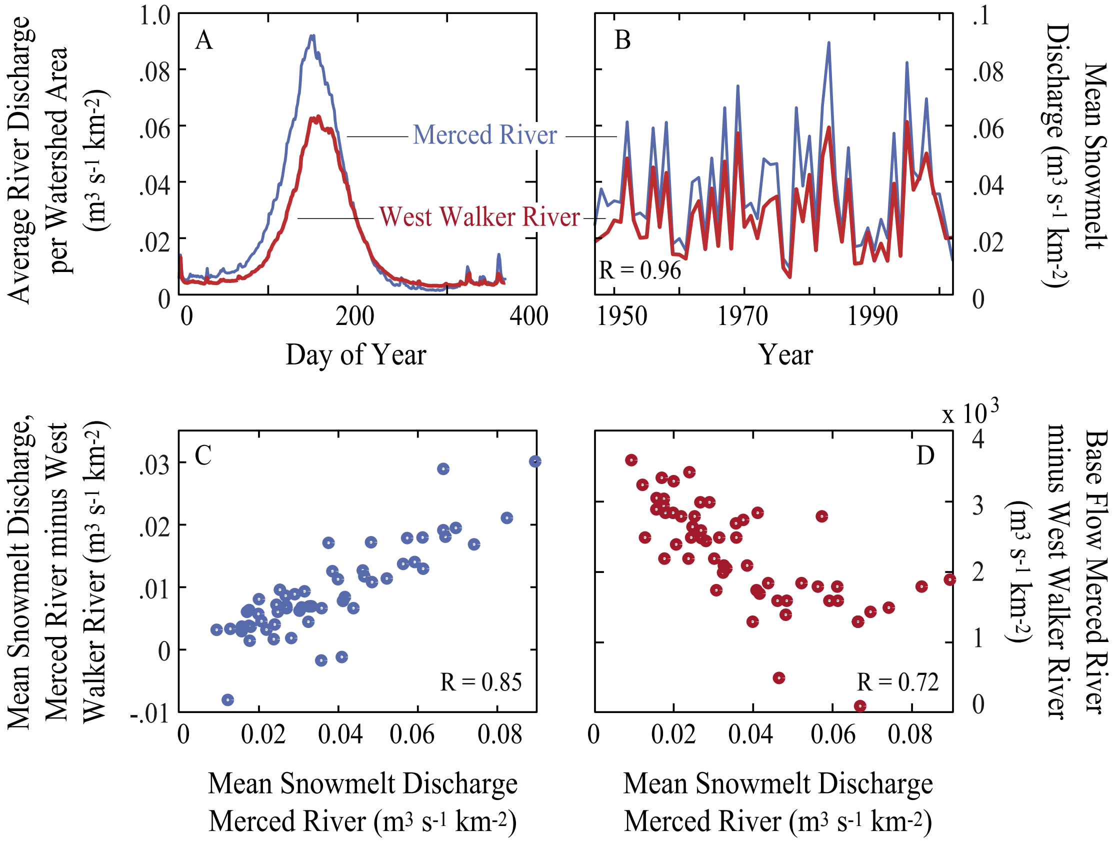


Figure 12. A) Long term mean discharge, Merced River at Happy Isles (blue) and West Walker River near Bridgeport (red), B) Merced River (blue) and West Walker River (red) mean annual snowmelt river discharge (averaged over days 105-275 to minimize rain contamination) 1948-2002, C) Merced minus West Walker mean annual snowmelt river discharge plotted against Merced River mean annual snowmelt river discharge, D) Merced River minus West Walker River base (low) flow plotted against Merced River mean annual snowmelt river discharge. Note the reversal in C and D correlations.

lower conductivity of base flow in the Merced River compared to the West Walker River (not shown). It is not yet clear if a difference in elevation or watershed surface exposure to solar insolation is also contributing to higher base flow in the West Walker, but this seems less likely from the similarity in exponential decline (hydrograph recession) in SMD between the two watersheds.

The results for the lower soil to bedrock ratio, Merced River vs. the higher soil to bedrock ratio, West Walker River (fig. 12, B, C and D) are consistent with the results for granitic Blackwood Creek vs. volcanic Trout Creek (fig. 11, B, C and D). However the correlations based on soil to bedrock ratio are not as strong as the correlations based on permeable vs. impermeable watersheds. This is expected because the differences are more subtle in the soil to bedrock ratio example than in permeable vs. impermeable watersheds.

FUTURE WORK

This analysis started with the Sierra Nevada, California, and will be extended across western U.S. A large-scale multi-watershed analysis provides information for scientists and managers (Cayan, et. al., 2005) that may be overlooked or less understood with a small-scale analysis (and vice versa). This work will include determining the watershed area as a function of elevation and estimate the area-weighted mean elevation; provide a more comprehensive analysis of the yearly variations in the spring pulse and center of mass timing and maximum daily snowmelt discharge and estimate the MDSMD timing and why the correlation in timing varies among watersheds, and identify an objective method for estimating base flow.

The most important limitation in this work is the absence of shallow well-water monitoring, to better define how snowmelt is partitioned between surface and ground water, and large scale estimates of evapotranspiration. This information is important to local water managers because an increasing population is accelerating the demand for ground water by installing numerous private and public wells along the western side of the Sierra Nevada. Another concern is that four of the twenty four river gages have been discontinued, and another is altered by human activity, which diminishes the documentation of the most important natural resource in California.

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APPENDIX A

Long term mean (climatology) of river discharge.

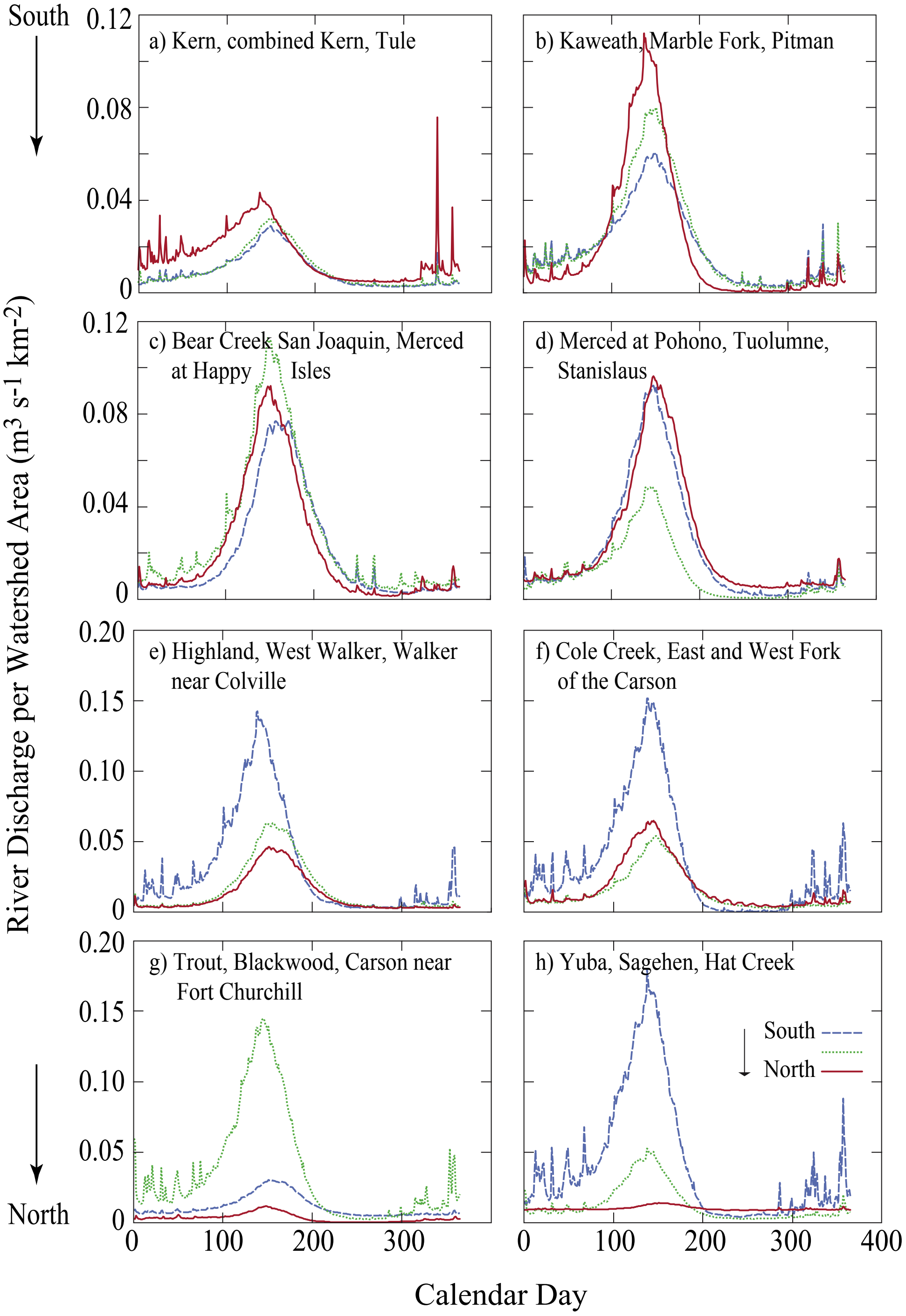
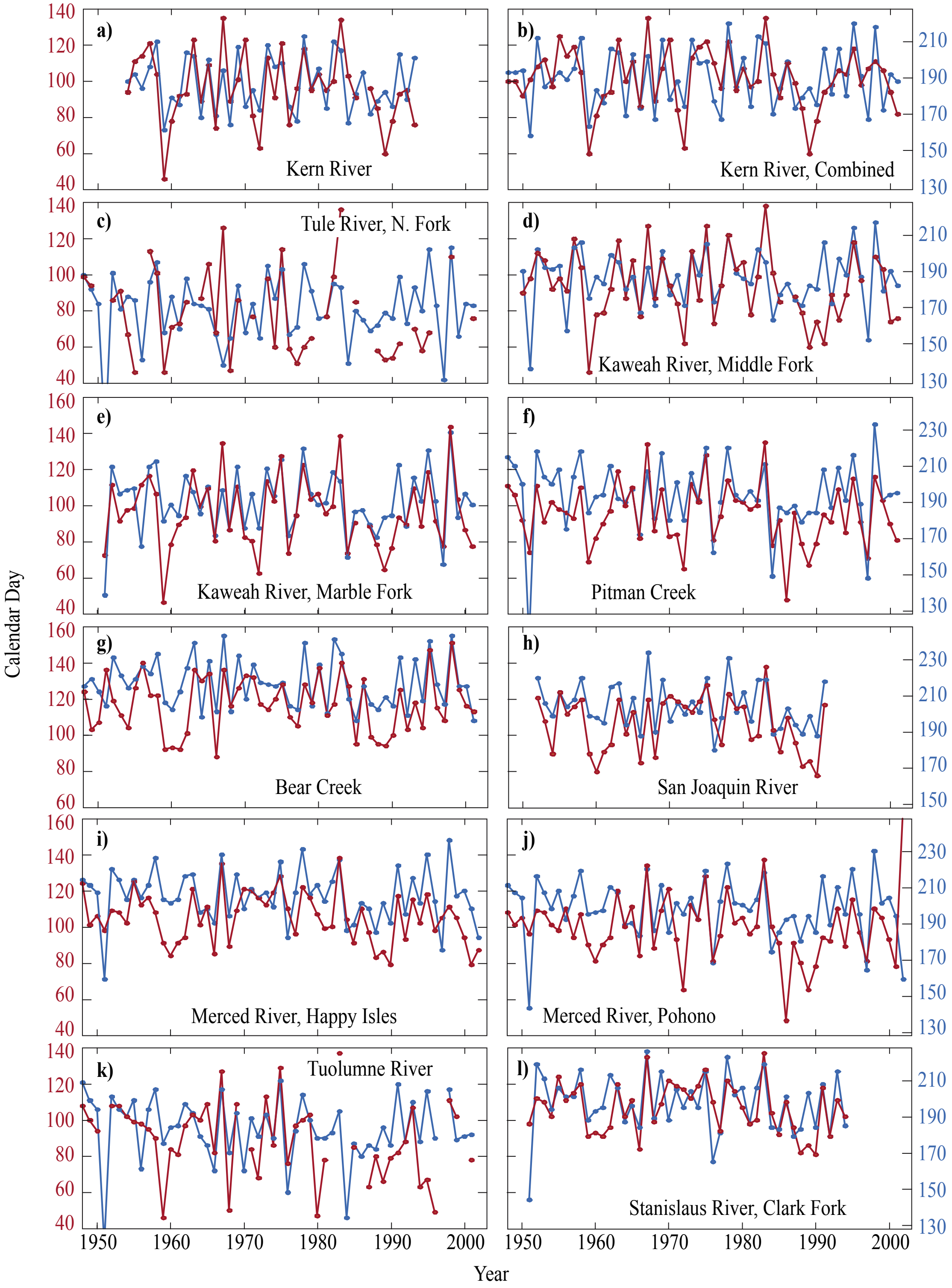


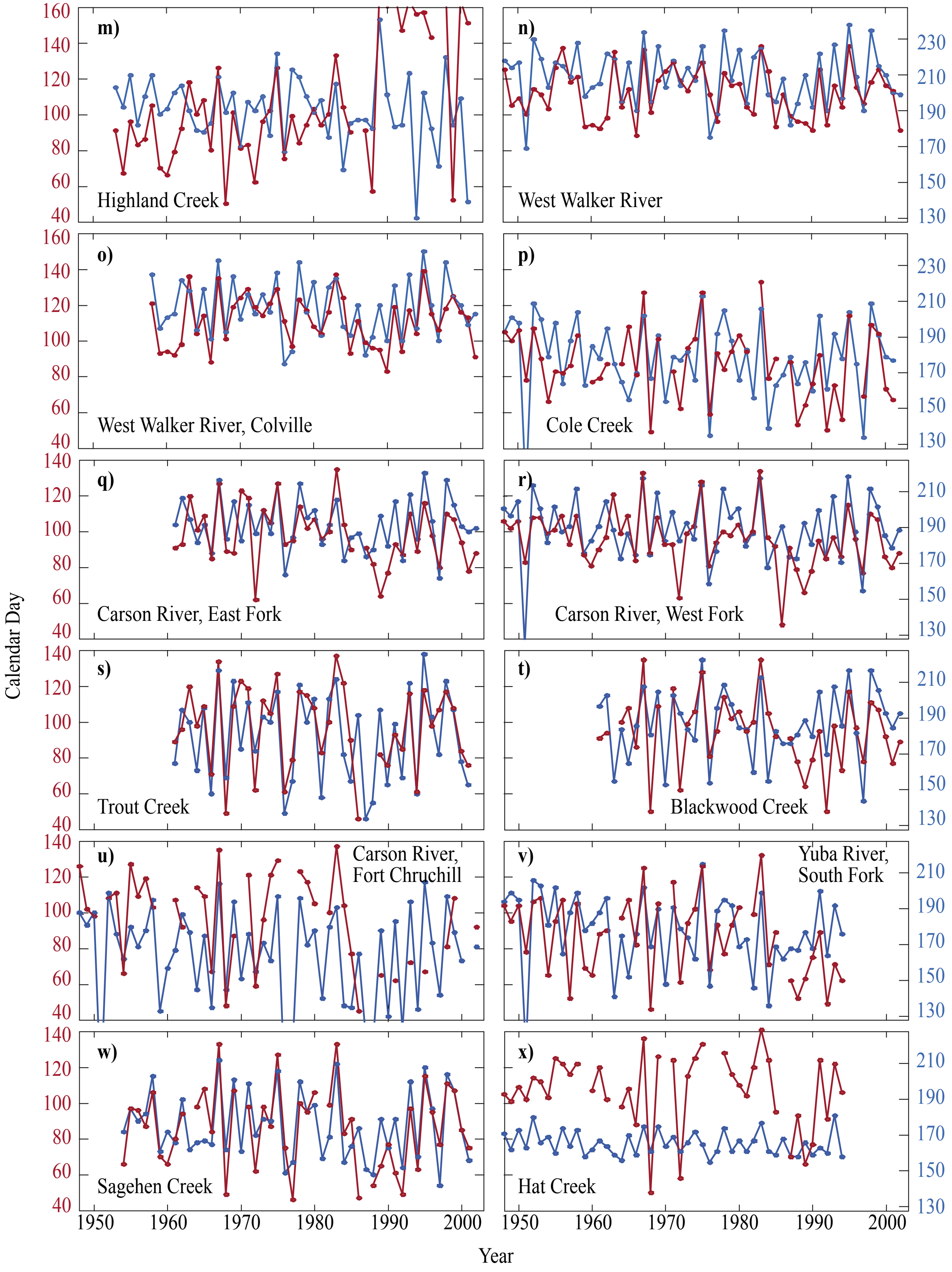
Figure A. Long-term daily mean of river discharge for the rivers and creeks in Fig. 1: a, Kern, combined Kern, and Tule; b, Kaweah, Marble Fork, and Pitman; c, Bear Creek, San Joaquin and Merced at Happy Isles; d, Merced at Pohono, Tuolumne, and Stanislous; e, Highland, West Walker, and Walker near Colville; f, Cole Creek, and East and West Fork of the Carson; g, Trout, Blackwood and Carson near Fort Churchill; h, Yuba, Sagehen, and Hat Creek. The order of presentation is from south to north along the Sierra Nevada and the spatial/color order for the three rivers or creeks in the panels is blue, green and red.

APPENDIX B

Individual trends in early snowmelt based on estimates of the spring pulse (red) and center of mass (blue).

Some of the sources of variability include the following: The center of mass is earlier in years with large winter floods (i.e., 1951); differences in record length (i.e., the slope of the trend increases if the time series ends in the early to mid 1990s, such as for the south fork of the Yuba River); human influences (i.e., Highland Creek after 1988 and the Carson River at Fort Churchill); results in years with wet winters and cool springs show similar responses for the two methods (i.e., 1967, 1975 and 1983).




m)
Highland Creek
n)
West Walker River
o)
West Walker River, Colville
p)
Cole Creek
q)
Carson River, East Fork
r)
Carson River, West Fork
s)
Trout Creek
t)
Blackwood Creek
u)
Carson River, Fort Chruchill
v)
Yuba River, South Fork
w)
Sagehen Creek
x)
Hat Creek
Calendar Day
Year
160
140
120
100
80
60
40
230
210
190
170
150
130
1950
1960
1970
1980
1990
2000

APPENDIX C

Maximum daily snowmelt discharge correlations with initial snow water equivalent (SWE)

TABLE 1 C. Statistics for Maximum Daily Snowmelt Discharge

River USGS Number	Snow Station	Start of SWE Record (year)	Regression Statistics (m)	(b)
Kern 11187000	205 Mammoth Pass	1961	3.00	-47.7
Kings	227 Woodchuck Meadow	1960	2.06	-18.4
Merced 11264500	176 Snow Flat	1930	1.09	18.7
West Walker 10296000	152 Sonora Pass	1937	1.40	10.3
West Carson 10310000	106 upper Carson Pass	1939	0.52	-1.05

The regression for maximum daily snowmelt discharge = m * SWE + b.

Should have a column for "n" – number of years used in regression, perhaps in lieu of Start of SWE Record. The regression for maximum daily snowmelt. Discharge = m * SWE + b..