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Principal Hydrologic Responses to Climatic and Geologic Variability in the Sierra Nevada, California

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ABSTRACT

Sierra Nevada snowpack is a critical water source for California's growing population and agricultural industry. However, because mountain winters and springs are warming, on average, precipitation as snowfall relative to rain is decreasing, and snowmelt is earlier. The changes are stronger at mid-elevations than at higher elevations. The result is that the water supply provided by snowpack is diminishing. In this paper, we describe principal hydrologic responses to climatic and spatial geologic variations as gleaned from a series of observations including snowpack, stream-flow, and bedrock geology. Our analysis focused on peak (maximum) and base (minimum) daily discharge of the annual snowmelt-driven hydrographs from 18 Sierra Nevada watersheds and 24 stream gage locations using standard correlation methods. Insights into the importance of the relative magnitudes of peak flow and soil water storage led us to develop a hydrologic classification of mountain watersheds based on runoff versus base flow as a percentage of peak flow. Our findings suggest that watersheds with a stronger base flow response store more soil water than watersheds with a stronger peak-flow response. Further, the influence of antecedent wet or dry years is greater in watersheds with high base flow, measured as a percentage of peak flow. The strong correlation between 1) the magnitude of peak flow, and 2) snow water equivalent can be used to predict peak flow weeks in advance. A weaker but similar correlation can be used to predict the magnitude of base flow months in advance. Most of the watersheds show a trend that peak flow is occurring earlier in the year.

KEYWORDS

Sierra Nevada, snowmelt, peak discharge, base flow prediction, climatic response

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INTRODUCTION

Climate is the major source of variability in the amount of available water resources. In the western U.S., for example, many rivers receive their largest contribution to annual flow from mountain snowpack, which melts in spring. Climate is the largest source of variability in the timing and the amount of this snowmelt-derived flow. Several studies have shown that warmer winter and spring temperatures are causing several concurrent factors that are affecting snowmelt-derived flow: increasingly earlier spring snowmelt runoff and earlier spring blooming (Cayan et al. 2001; Stewart et al. 2005), a diminishing snowpack, and a decrease in winter snow relative to rain (Dettinger and Cayan, 1995; Mote 2003; Dettinger 2005; Mote et al. 2005; Knowles et al. 2006).

These hydro-climatic trends are motivating researchers to predict the long-term rise in air temperature and its hydro-climatic consequences (Knowles and Cayan 2002; 2004; Dettinger et al. 2004) such as earlier snowmelt (Stewart et al. 2004), less snow (Barnett et al. 2005); alpine forest change (Hayhoe et al. 2004) and, possibly, even less runoff (Milly et al. 2005). As the warming trends and their effects on western water resources are likely to continue, observational hydro-climatic networks, as well as simulation and prediction efforts, are an important contribution to understanding, forecasting, and, if possible, mitigating the effects of warming trends on snowmelt discharge and water resources.

To understand large-scale alpine linkages, processes, and responses, a comprehensive study of western US snowmelt-driven river discharge and watershed characteristics is necessary. Studies of these high-elevation watersheds are important because the watersheds supply a large proportion of water resources, and are often more susceptible to climatic changes and have fewer human influences than low-elevation watersheds. The initial effort described here focuses on the Sierra Nevada mountain range in California as an important water resource for a large population.

We studied snowmelt discharge (SMD) responses to climatic and spatial geologic variations in 18 watersheds. Major topics, based mostly on historical river discharge observations, are as follows: 1) the inter-basin correlations in snowmelt river discharge and the intra-basin correlations of peak and base flow; 2) the trend toward earlier snowmelt based on when the spring pulse starts (the first major surge in snowmelt discharge (Cayan et al. 1999), the center of mass (Stewart et al. 2005), and when snowmelt discharge peaks; 3) the geologic influence on hydrology, based largely on inter-basin differences in peak (maximum) and base (minimum) flow responses to increasing snowmelt discharge; and 4) prediction of peak and base flow amplitude as a linear function of initial snow water equivalent (snowpack depth converted to snow water equivalent) sampled annually on or near April 1.

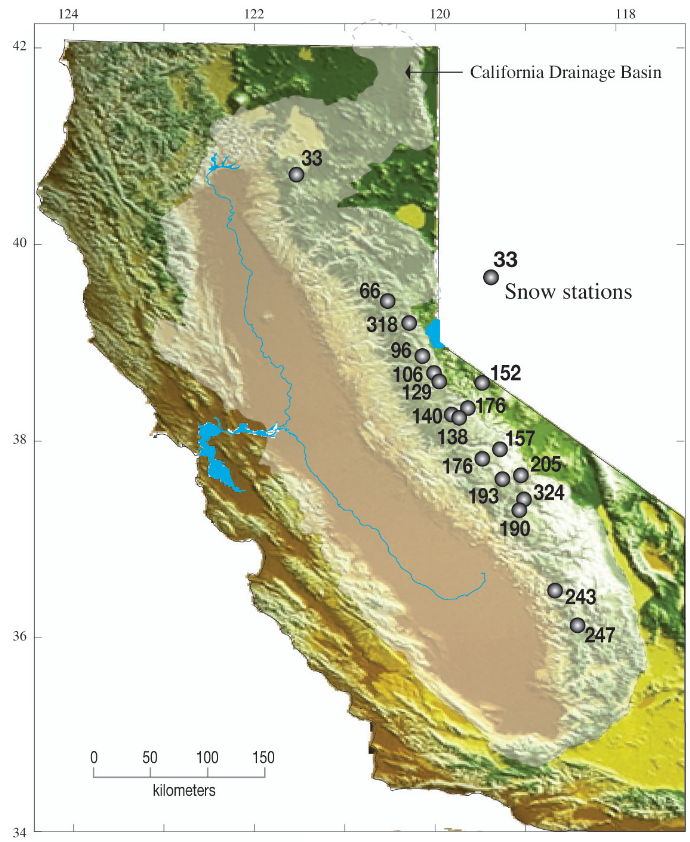

Figure 1. The snow course locations . The snow course numbers in the Figure are matched to the watersheds listed in Table 1.

This report provides data sources, definitions and methods, and a brief introduction to California hydroclimatology. Results of this study include trends

Table 1. RIVER BASINS AND THEIR RESPECTIVE SNOW STATIONS

River Basin	Snow Station		Elevation (Meters)	Start of Record
Kern at Kernville	205	Mammoth Pass	2,830	3/1928
Combined Kern	205	Mammoth Pass	2,830	3/1928
North Fork Tule	247	Quaking Aspen	2,130	4/1937
Middle Fork Kaweah	243	Panther Meadow	2,620	3/1925
Marble Fork Kaweah	243	Panther Meadow	2,620	3/925
Pitman Creek	190	Kaiser Pass	2,770	4/1930
Bear Creek	324	Lake Thomas Edison	2,380	2/1958
San Joaquin at Millers Crossing	193	Cora Lakes	2,560	4/1939
Merced at Happy Isles	176	Snow Flat	2,650	2/1930
Merced at Pohono	176	Snow Flat	2,650	2/1930
Middle Fork Tuolumne	157	Dana Meadows	2,990	1/1926
Stanislaus at Clark Fork	138	Lower Relief Valley	2,470	5/1930
Highland Creek	140	Eagle Meadow	2,270	3/1931
West Walker	152	Sonora Pass	2,670	4/1930
West Walker near Colville	152	Sonora Pass	2,670	4/1930
Cole Creek	129	Blue Lakes	2,440	4/1918
East Fork Carson	106	Upper Carson Pass	2,600	1/1930
West Fork Carson	106	Upper Carson Pass	2,600	1/1930
Trout Creek	96	Lake Lucille	2,500	4/1916
Blackwood Creek	318	Squaw Valley	2,350	3/1954
Carson near Fort Churchill	106	Upper Carson Pass	2,590	1/1930
South Yuba	66	Meadow Lake	2,190	4/1920
Sagehen Creek	318	Squaw Valley	2,350	3/1954
Hat Creek	33	Thousand Lakes	1,980	3/1946

toward earlier snowmelt in the Sierra Nevada; inter- and intra-basin response differences in peak and base flow to increasing snowmelt discharge; plots indicating the annual maximum and minimum in daily amplitude and timing for forecasting via two methods; and implications of the results, including a work-in-progress conceptual model of snowmelt discharge.

DATA SOURCES, DEFINITIONS, AND METHODS

Snowpack observation locations are shown in Figure 1. Pertinent information about the snow stations is provided in Table 1. The California snow course and sensor data are from the California Department of Water Resource's (CDWR's) California Data Exchange Center (CDEC) website (http://cdec.water.ca.gov/). River discharge gage locations are shown in Figure 2 and described in Table 2. Data are from the U.S. Geological Survey (USGS) Hydro-climatic Data Network (HCDN) (Slack and Landwehr 1992).

The selection criteria for snowmelt-driven watersheds are described by Stewart et al. (2005). Mean annual flows are calculated for the calendar year (January 1–December 31). Calculation of the timing of the start of the spring pulse is described in Cayan et al. (2001). Peak flow is the maximum in mean daily snowmelt

Table 2. RIVER GAGES

	Station Name	USGS Number	Gage Elevation (meters)	Area (km^2)	Years
1	Kern at Kernville	11187000	799	2,613	1912 - present
2	Combined Kern	11186001	1,103	2,191	1961 - present
3	North Fork Tule	11202001	890	101.8	1940 - present
4	Middle Fork Kaweah	11206501	640	264.2	1949 - present
5	Marble Fork Kaweah	11208001	655	133.1	1950 - present
6	Pitman Creek	11237500	2,140	59.3	1927 - present
7	Bear Creek	11230500	2,245	136	1948 - present
8	San Joaquin at Millers Crossing[1]	11226500	1,392	644.9	1951 - 1991
9	Merced at Happy Isles	11264500	1,224	468.8	1915 - present
10	Merced at Pohono	11266500	1,177	831.4	1916 - present
11	Middle Fork Tuolumne	11282000	853	190.4	1916 - present
12	Stanislaus at Clark Fork[1]	11292500	1,679	174.8	1950 - 1994
13	Highland Creek[2]	11294000	1,932	119.1	1952 - present
14	West Walker	10296000	2,009	468.9	1938 - present
15	West Walker near Coleville	10296500	1,683	640.1	1957 - present
16	Cole Creek	11315000	1,804	54.4	1943 - present
17	East Fork Carson	10308200	1,646	714.8	1960 - present
18	West Fork Carson	10310000	1,754	169.4	1938 - present
19	Trout Creek	10336780	1,902	95.1	1960 - present
20	Blackwood Creek	10336660	1,900	29.0	1960 - present
21	Carson near Fort Churchill	10312000	1,285	3,372	1911 - present
22	South Yuba[1]	11414000	1,683	134.2	1942 -1994
23	Sagehen Creek	10343500	1,926	27.2	1953 - present
24	Hat Creek[1]	11355500	1,311	419.6	1930 - 1994

[1] *Discontinued.*
[2] *Record altered 1989 to present.*

discharge following the spring pulse. Base flow is the minimum in river discharge following peak flow. Snowmelt discharge climatology (Appendix A, http://sfbay.wr.usgs.gov/hydroclimate/alpine/Sierra.html) is the long-term river discharge normalized to the area above the gage for the 24 gage locations.

Trends in the timing of the spring pulse and the center of mass of river discharge (Cayan et al. 2001; Stewart et al. 2004; 2005) were determined from historical stream-flow records as described by Cayan et al. (1999; 2001) and Stewart et al. (2004; 2005). These references include details on the statistical method used to estimate the earlier timing. Statistical parameters of the linear regression between initial snowpack and mean annual snowmelt river discharge (MASMD)—arbitrarily estimated as mean discharge over days 100–250, unless otherwise stated—were estimated by standard methods (Peterson et al. 2002). The distance of river gages from the gage on the Merced River at Happy Isles was computed from the haversine formula. Bedrock geology was estimated from the geologic maps cited in Table 3.

Table 3. GEOLOGIC DESCRIPTIONS OF WATERSHED BEDROCK

	Watershed [1]	Geologic Map[2]	Quaternary Alluvium	Quaternary Glacial Till and Outwah	Quaternary Volcanic	Tertiary Intrusives Hypabyssal	Tertiary Volcanic	Tertiary Volcanic Sediments	Mesozoic Crystalline	Pre-K Metamorphic	Paleozoic Metamorphic
1	Kern at Kernville	(a)		2			1		92	5	
2	Combined Kern	Similar to watershed 1									
3	North Fork Tule	(b)	1						50	49	
4	Middle Fork Kaweah	(b)	1			1			91	7	
5	Marble Fork Kaweah	(b)		5					85	10	
6	Pitman Creek	(c)		20					80		
7	Bear Creek	(c)		5		2			90	3	
8	San Joaquin at Millers Crossing	(c)		5	5	5	.		55	30	
9	Merced at Happy Isles	(c)	1	15					80	4	
10	Merced at Pohono	(c)	1	15					81	3	
11	Middle Fork Tuolumne	(c)	8						90		2
12	Stanislaus at Clark Fork	(d)	3			2	30		65		
13	Highland Creek	(d)	1	4		10	10		75		
14	West Walker	(d)	5	15			40		35	5	
15	West Walker near Coleville	(d)	4	12			44		32	8	
16	Cole Creek	(e)		5				5	90		
17	East Fork Carson	(d)	3	1		2	50		42	2	
18	West Fork Carson	(d)	7	1		1	30		54	7	
19	Trout Creek	(f)	2	21					77		
20	Blackwood Creek	(g)		40	10		40	3		10	
21	Carson near Fort Churchill	(h)	16			2	44		30	5	
22	South Yuba	(g)		22			10		55	12	1
23	Sagehen Creek	(g)		55			45				
24	Hat Creek	(a)			100						

[1] *Listed from south to north as per Table 2.*
[2] *Geologic map references*

(b) Campbell	*1966*
(c) Campbell	*1967*
(d) Campbell	*1963*
(g) Davis	*1992*
(e) Davis	*1981*
(a) Jennings	*1977*
(f) Saucedo	*2005*
(h) Stewart, JH	*1978*

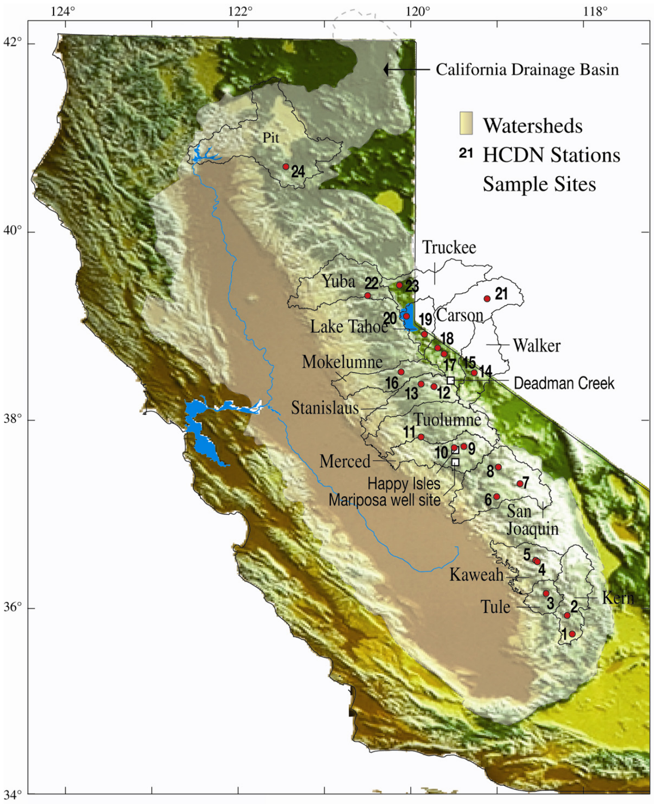

Figure 2. River discharge gage locations (red dot) in the Sierra Nevada, California. River gage information is in Table 2.

RESULTS AND DISCUSSION

Hydrologic Responses to Climatic Variations

California Hydroclimatology

California has a Mediterranean climate with wet winters and dry summers. Mountain air temperatures decrease with increasing elevation. 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. Moist air loses its moisture (through rain or snow) and cools as it ascends the mountain range from the west. The east side of the mountain range is dryer than the west side due to the effects of this "rain shadow." Because the air is descending and warming over the eastern flank of the Sierra Nevada, it releases less moisture (Powell and Klieforth 2000). California climate and water are described in more detail in the California Water Atlas (Kahrl 1978).

There are three major features of the annual Sierra Nevada snowmelt discharge hydrograph: the spring pulse, the peak flow, and the base flow. The spring pulse is the winter–spring transition or the start of the first large response to an increase in temperature that first ripens the snowpack (fills porous snowpack with snowmelt), and then triggers the surge in snowmelt discharge. The peak flow is the maximum amplitude in daily snowmelt discharge following the spring pulse. The base flow is the minimum amplitude in daily discharge following peak flow. Generally, spring pulse is in mid-April, peak flow is in late May or early June, and base flow typically resumes in September or October.

Figure 3 shows the three major features of the snowmelt discharge hydrograph for the Merced River at Happy Isles in Yosemite National Park. Note that air temperature (red) is the same scale as river discharge (blue), but in degrees centigrade. In 1999 (a typical year), the start of the spring pulse was on April 16 (day 106). The timing of the spring pulse is typically influenced more by air temperature than by the size of the initial snowpack (snow depth or snow water equivalent [SWE]) on or near April 1).

In 1999 (Figure 3), peak flow was less than two months later, on May 28 (day 146). The magnitude of peak flow is influenced more by initial SWE than by air temperature (Peterson et al. 2004). A large initial SWE is more likely to result in a high-amplitude (and delayed) peak flow than a small initial SWE (which is delayed partly because it takes more time to melt more snow). Snowmelt often lags (i.e., peaks later than) air temperature. The last major peak following the highest peak typically has a lower response but at a higher air temperature than the highest peak. This indicates that snow cover is diminishing and is limiting the air temperature response.

In 1999 (Figure 3), a return to base flow took place almost seven months later on October 26 (day 299). Base flow is sustained by, and a measure of, shallow ground water.

Inter-basin Differences in Snowmelt Discharge

Snowmelt–discharge trends were developed for 23 alpine watershed gages and compared to snowmelt–discharge trends in Merced River at Happy Isles in Yosemite National Park. As shown in Figure 2, the Happy Isles station is located at roughly the north–south midpoint of all of the stations. The Merced River at Happy Isles was selected as the reference for correlation because of its long and continuous discharge record and central location.

As shown in Figure 4, the correlation in inter-basin mean annual snowmelt discharge decreases with distance from Happy Isles, but is strong within 200 kilometers south and north. Major exceptions are Cole Creek (slightly north of Happy Isles) and Hat Creek (which is located significantly farther north than the other stations). The strong correlations of mean annual snowmelt discharge are important to note within the context of basin-to-basin differences in the timing of this discharge, illustrating that a climatic – rather than geologic – perspective is a helpful starting point to unravel inter-basin hydrologic responses. As discussed later, climatic variation tends to bring out similarity in basin-to-basin snowmelt discharge and geologic variation differences.

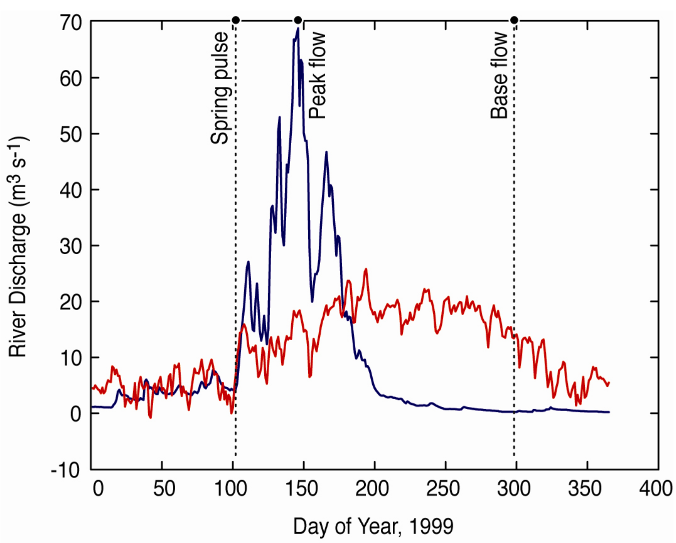

Figure 3. Three major features of the snowmelt discharge hydrograph, spring pulse, peak flow and base flow, Merced River at Happy Isles , Yosemite National Park. Note that air temperature (red) is the same scale as river discharge (blue), but in degrees centigrade. In a typical year, 1999, the start of the spring pulse was on April 16 (day 106), peak flow was less than 2 months later at Happy Isles, on May 28 (day 146), and a return to base flow took place almost 7 months later on October 26 (day 299). Note that snowmelt often lags (peaks later than) air temperature. Also note that the last major peak, following the highest peak, has a lower response but at a higher air temperature than the highest peak. This indicates snow cover is diminishing, and limiting the air temperature response.

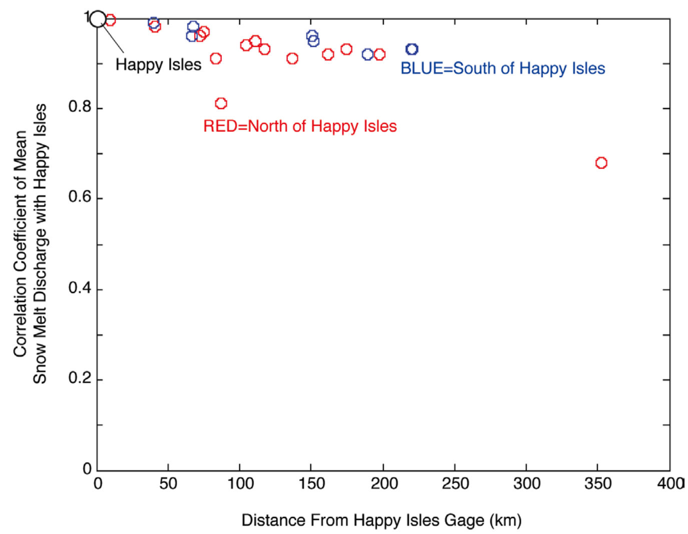

Figure 4. Correlations in mean annual snowmelt discharge Merced River, Happy Isles, Yosemite National Park with respect to distance south (blue) and north (red) of Happy Isles. The first anomalous red circle (before 100 kilometers) is Cole Creek and the last is Hat Creek.

Variations in daily SMD strongly correlate with variations in air temperature (Figure 3). Because alpine temperature variations are large-scale, SMD variations are large-scale, cutting across many watersheds (Peterson et al. 2000). The correlations in discharge between watersheds are stronger in wet winters, when snowpack is widespread, and weaker in dry winters, when snowpack is not widespread (Figure 5). Two watersheds are uncorrelated in the dry year. Hat Creek is underlain with volcanic rock, which has a high rate of snowmelt infiltration. The Carson River at Fort Churchill is influenced by upstream agricultural diversion and possibly by a low water table. These influences on surface river discharge are also greater in a dry than wet year.

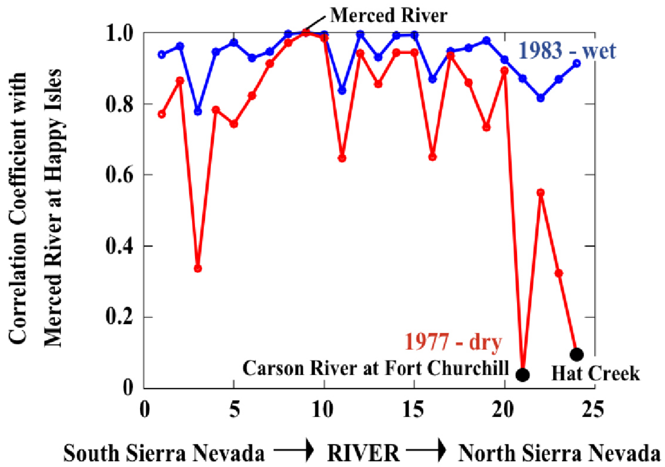

Figure 5. Correlation coefficients of daily discharge in rivers of the Sierra Nevada with that of the Merced River at Happy Isles, Yosemite National Park for a wet (1983, blue) and dry (1977, red) year arranged from south to north (as in Table 1, starting from the top). The mean correlation coefficient, R, is 0.93 +/- .09 in the wet year and 0.72 = +/- .24 in the dry year, the latter largely due to the Carson River at Churchill and Hat Creek. The Merced River at Happy Isles was selected as the reference for correlation because of its long and continuing discharge record and its central location.

Figure 6 shows daily Sierra Nevada snowmelt runoff discharge normalized to the watershed area above the river discharge gage in a wet year (1983, A) and in a dry year (1977, B). The south–to–north increase in runoff is especially distinct in the wet year. Also, the difference in runoff between the wet and dry years is almost an order of magnitude; note the vertical scales change between A and B. Note also the sharp winter rain-derived river discharge peaks near the end of the wet and dry years. In these two El Nino Southern Oscillation (ENSO) years, the relative amount of rain appears to increase from south to north in the wet year (upper graph), and appears uniform in the dry year (lower graph)

Considering mean annual snowmelt discharge, peak and base flows (Figure 7), it is clear that, in general, inter-basin correlations are stronger in discharge magnitude (upper panel) and weaker in discharge timing (lower panel). Using the Merced River at Happy Isles does not necessarily represent the most likely watershed variations in the Sierra Nevada, for examples (not shown) of base flow correlations of paired watersheds: Trout Creek and the combined Kern River R = 0.84; the West Walker River near Coleville and the west fork of the Carson, R = 0.88; the Stanislaus River at Clark fork and the West Walker near Coleville, R = 0.89; the west fork of the Carson and the Stanislaus at Clark fork, R = 0.84; the West Walker and the middle fork of the Kaweah River, R=0.85; the West Walker and the east fork of the Carson River, R = 0.94; and the San Joaquin River at Miller's Crossing and Bear Creek, R = 0.96. Why these, and likely other correlations, are strong is a subject for research.

Intra–Basin Discharge

Similar to the basin–to–basin correlations, the correlations of the magnitude of intra-basin flow measures are stronger than the correlations for the timing of the flow measures (Figure 8). In general, peak flow

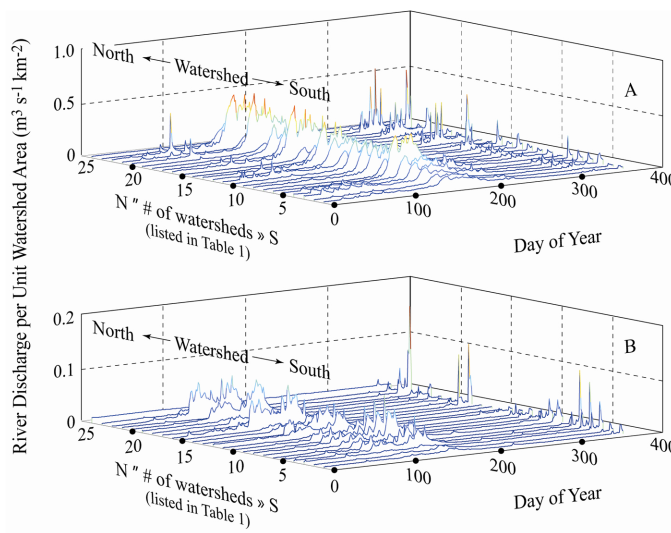

Figure 6. Daily south-to-north Sierra Nevada snowmelt runoff (discharge normalized to the watershed area above the river discharge gage) in a wet year, 1983 (panel A), and in a dry year, 1977(panel B). The south-to-north increase in runoff is especially distinct in the wet year. Also the difference in runoff between the wet and dry years is almost an order-of-magnitude (the vertical scales change between A and B). Note the sharp winter rain-derived river discharge peaks near the end of the wet and dry years. In these two ENSO years, the relative amount of rain appears to increase from south to north in the wet year (upper graph) and appears uniform in the dry year (lower graph).

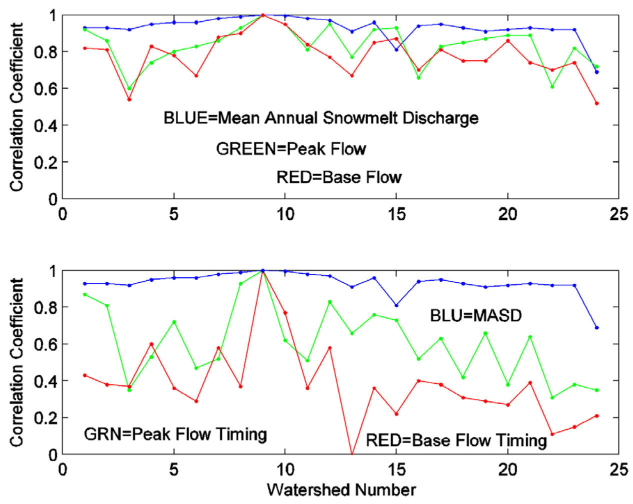

Figure 7. Upper panel: the inter-basin correlation in mean annual snowmelt river discharge with the Merced River at Happy Isles (blue) is as in Figure 4, but the watersheds are ordered from south to north by number as in Table 2. The correlations in peak (green) and base (red) flows are with the peak and base flows at Happy Isles. Lower panel: the same as in the upper panel, but for peak flow (green) and base flow (red) flow timing. The inter-basin correlations in mean annual snowmelt river discharge (blue) are included for reference.

magnitude is better correlated to mean annual flow than either base flow magnitude to mean annual flow or peak flow to base flow magnitude. For some watersheds, the relationship between all three flow measures is strong. The strong correlations between peak flow and base flow are from the two Kern River sites, the Stanislaus River at Clark Fork, the East and West Forks of the Carson Rivers and Trout Creek; these are all rivers with relatively high base flow compared to peak flow. Conversely, the Highland Creek, Cole Creek, and Yuba River had weak or no correlation between base flow and mean annual snowmelt river discharge; these streams have a large number of near-zero base flow values.

The statistics in Table 4 represent very high correlation coefficients with respect to mean annual snowmelt discharge (MASMD). In a prediction mode, when the correlation is with SWE, the correlations would be weaker.

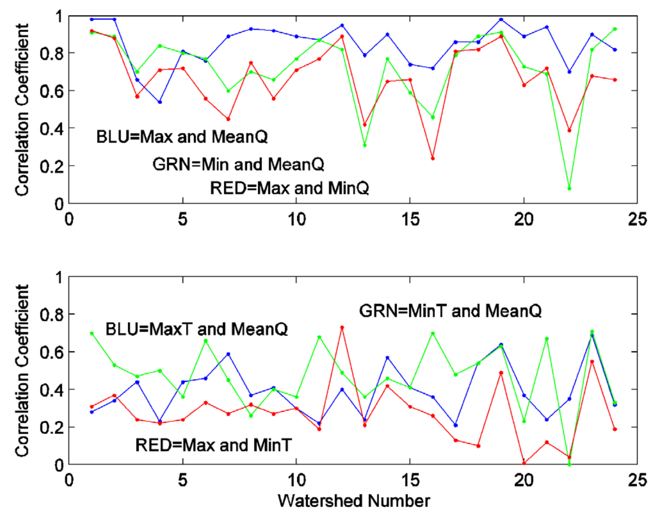

Figure 8. Upper panel: the intra-basin (within the watershed) correlation of (A) peak flow magnitude with mean annual snowmelt river discharge (blue), (B) base flow magnitude with mean annual snowmelt river discharge (green), and (C) peak flow magnitude with base flow magnitude (red). Lower panel: the same as above, but for timing in peak flow (blue) and base flow (green) with mean annual snowmelt river discharge, and the correlation in peak and base flow timing (red).

Trends in Timing

The progression toward earlier snowmelt across North America (Cayan et al. 2001) is determined by comparing the historical timing trends of the start of the spring pulse with the center of mass of streamflow timing (Stewart et al. 2004; 2005). In the Sierra Nevada, the spring pulse (Figure 9) exhibits a statistically stronger and spatially more extensive early melt pattern than the center of mass (Figure 10). The center of mass timing is water-year-based (meaning that it starts on October 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. (See also Appendix B, http://sfbay.wr.usgs.gov/hydroclimate/alpine/Sierra.html)

The long-term trend in timing of peak flow appears to be another – but probably less sensitive – measure of early snowmelt (Figure 11). Trends in the timing and magnitude of peak flow are shown in Table 5 (see also Peterson et al. 2005). In general, the timing of peak flow is earlier (and the magnitude is increas-

Table 4. STATISTICS OF PEAK AND BASE FLOWS AS A LINEAR FUNCTION OF MEAN ANNUAL RIVER DISCHARGE

		Peak			Base		
River Gage No.	Watershed	Correlation Coefficient (R)	Slope	Intercept	Correlation Coefficient (R)	Slope	Intercept
1	Kern at Kernville	0.97	2.098	6.986	0.81	0.0669	2.05
2	Combined Kern	0.98	1.961	10.230	0.89	0.0625	2.40
3	North Fork Tule	0.66	2.606	0.3030	0.77	0.0574	0.210
4	Middle Fork Kaweah	0.84	2.235	2.576	0.84	0.0353	0.130
5	Marble Fork Kaweah	0.81	2.287	2.960	0.81	0.0230	0.0101
6	Pitman Creek	0.76	3.185	1.857	0.77	0.0073	-0.0079
7	Bear Creek	0.89	2.257	2.935	0.60	0.0304	0.0056
8	San Joaquin at Millers Crossing	0.93	2.282	12.524	0.70	0.0303	0.395
9	Merced at Happy Isles	0.92	2.202	15.780	0.65	0.0146	-0.0748
10	Merced at Pohono	0.89	2.295	22.774	0.77	0.0148	0.0914
11	Middle Fork Tuolumne	0.87	2.879	1.555	0.87	0.0190	-0.0279
12	Stanislaus at Clark Fork	0.95	2.080	4.440	0.82	0.0482	0.233
13	Highland Creek	0.81	3.200	1.087	0.31	0.0043	0.011
14	West Walker	0.90	2.233	7.708	0.77	0.0434	0.202
15	West Walker near Coleville	0.94	2.220	6.261	0.75	0.0495	0.348
16	Cole Creek	0.72	3.650	2.051	0.46[1]	0.0018	-0.00034
17	East Fork Carson	0.79	3.161	-5.435	0.86	0.0522	0.332
18	West Fork Carson	0.86	2.625	1.214	0.89	0.0586	0.126
19	Trout Creek	0.98	2.048	0.028	0.91	0.160	0.060
20	Blackwood Creek	0.89	3.052	0.393	0.72	0.0173	0.0172
21	Carson near Fort Churchill	0.94	2.444	10.779	0.69	0.0285	-0.315
22	South Yuba	0.74	2.537	11.633	0.07[1]	0.0027	0.209
23	Sagehen Creek	0.82	3.170	0.051	0.90	0.0501	0.0315
24	Hat Creek	0.84	1.680	-1.001	0.91	0.553	0.826
	Mean (+/- Std.)	0.86 (0.086)	2.52 (0.50)	4.99 (6.32)	0.80 (0.089)	0.68 (0.12)	0.068 (0.116)

[1] *Base flow corrupted and not part of the statistical values given below.*

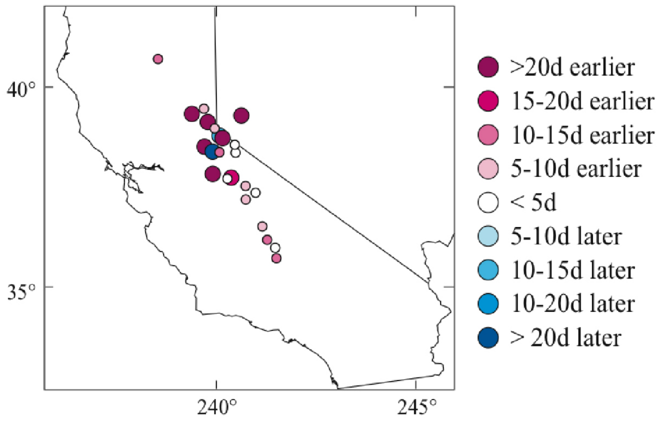

Figure 9. Trends (1948–2002) in snowmelt discharge timing, based on the start of the spring pulse. For example, a 15- to 20-day earlier trend means the linear trend estimate in the timing of the spring pulse starting in 1948 was 15 to 20 days earlier in 2002. Large circles are trends that are statistically significant at the 95% confidence level; small circles are not statistically significant.

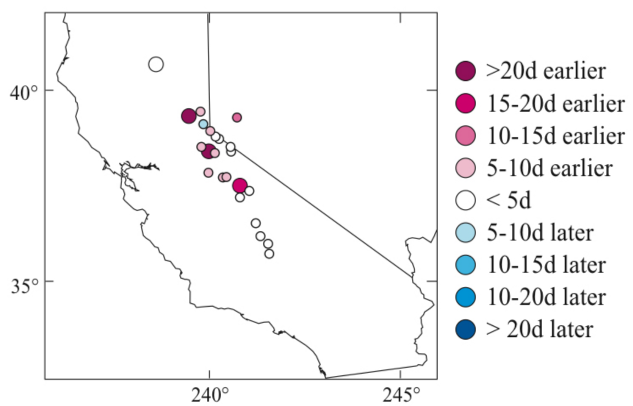

Figure 10. Trends (1948–2002) in snowmelt discharge timing, based on the center of mass, with the same timing interpretation as in Figure 4. Large circles are trends that are significant at the 95% confidence level; small circles are not statistically significant.

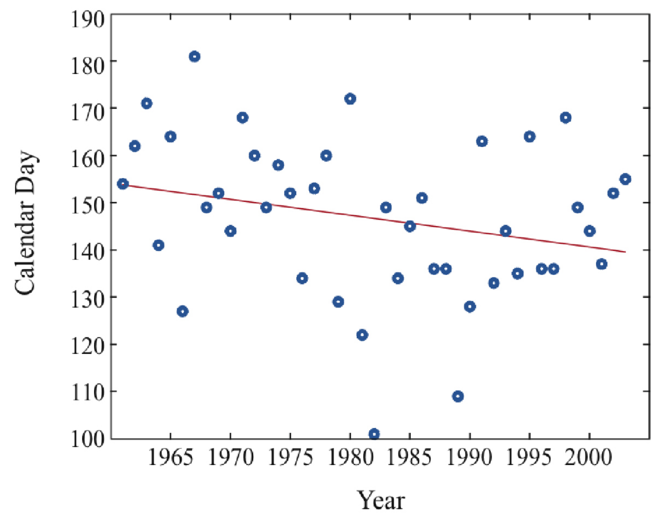

Figure 11. Trend in the timing of snowmelt discharge based on the day of maximum daily discharge (peak flow), Kern River.

ing). Some inter-basin differences may be partly the result of differences in record length and timing. The Tule River, Bear Creek, Highland Creek, and Yuba River had late, rather than early, timing of peak flow (Note that the number of significant figures in Table 5 are not statistically valid, but given for calculation purposes).

Hydrologic Responses to Spatial Geologic Variations

Numerous publications describe the geology of the Sierra Nevada; the two cited here are Huber (1989) and Moore (2000). The watershed bedrock geology for each basin (in %) listed in Table 3 constrains bedrock permeability; however, additional information is needed to better access geologic variations, including the degree of consolidation. Glacial history (Guyton 1998; Moore 2000; Huber 1989), a major influence on soil thickness, is inferred from inter- and intra-basin differences in annual hydrographs, and from peak and base flow time series and magnitudes in response to variations in wetness and dryness.

In studying base flow, mean soil thickness seems more important than bedrock geology in distinguishing hydrologic differences (with the exception of Hat Creek) because of the widespread granite in the Sierra Nevada. The Yuba River, and, therefore, prob-

Table 5. TRENDS IN THE TIMING AND MAGNITUDE OF PEAK FLOW[1]

		Timing		Discharge	
Watershed	**Period of Record**	**Days per year**	**Days over period of record**	**Cubic meters per second per year**	**Cubic meters per second over period of record**
Kern at Kernville	1954-1992	-0.323	-11.3	0.258	9.02
Combined Kern	1947-2000	-0.054	-2.67	0.91	44.8
North Fork Tule	1947-2000	0.227	11.4	Very small decrease	
Middle Fork Kaweah	1950-2000	-0.119	-5.96	0.097	4.84
Marble Fork Kaweah	1951-2000	-0.033	-1.65	0.065	3.24
Pitman Creek	1947-2000	-0.101	-5.02	0.123	6.15
Bear Creek	1947-2000	0.043	2.14	0.067	3.5
San Joaquin at Millers Crossing	1952-1990	-0.644	-22.5	Small decrease	
Merced at Happy Isles	1947-2002	-0.187	-9.36	0.100	5.01
Merced at Pohono	1947-2000	-0.044	-2.19	0.551	27.5
Middle Fork Tuolumne	1947-1995	-0.055	-2.48	0.052	2.3
Stanislaus at Clark Fork	1951-1993	-0.350	-12.2	-0.117	-4.1
Highland Creek	1953-1988	0.891	45	-0.120	-5.4
West Walker	1947-2002	-0.194	-10.99	0.132	7.38
West Walker near Coleville	1958-2002	-0.280	-12.3	0.272	12.0
Cole Creek	1947-2000	-0.182	-9.1	0.127	6.36
East Fork Carson	1961-2002	-0.091	-3.73	0.253	10.6
West Fork Carson	1947-2002	-0.106	-5.84	0.064	3.50
Trout Creek	1961-2000	-0.610	-23.7	0.020	0.77
Blackwood Creek	1961-2000	-0.260	-10.2	0.061	2.39
Carson near Fort Churchill	1947-1999	-0.232	-12.1	0.393	20.5
South Yuba	1947-1978	0.42	12.9	0.26	8.2
Sagehen Creek	1954-2000	Very small decrease		0.502	45.0
Hat Creek	1947-1991	-0.03	-1.2	-0.009	-0.04

[1] *A negative value means earlier peak flow timing or a decrease in peak flow over the trend on an annual basis or for the period of record.*

ably other Sierra Nevada river landscapes, may be 40 to 50 million years old, based on the hydrogen isotopic composition of kaolinite from Eocene fluvial sediments (Mulch et al. 2006). A general text on hydrology is Pielou (1989), and a text specifically on California hydrology is Mount (1995).

Peak Flow

The response of peak flow to increasing mean discharge over days 100–250 is assessed by plotting peak flow versus increasing mean discharge and then calculating slope of the line. Greater slope values correspond to a greater response. When the slope is plotted against watershed size (Figure 12), the greatest slope values (i.e. responses) are for the smallest watersheds, suggesting that as the size of the watershed increases, the system becomes more “sluggish.”

Another influencing factor is water storage (discussed below in the peak versus base flow section). Trout

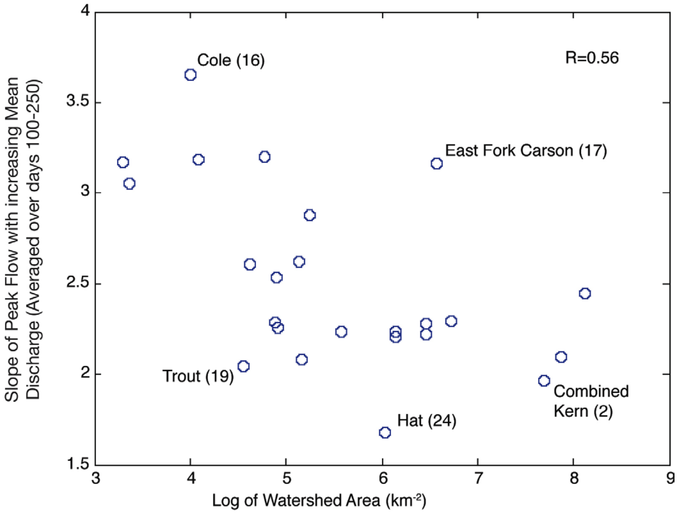

Figure 12. Watershed response (as measured by the slope of the line when peak flow is plotted versus increasing mean discharge over water year days 100–250) versus watershed size.

and Hat Creeks have the highest base flow as a percentage of peak flow, and presumably a high groundwater component, resulting in a relatively small slope compared to watershed size. However, the East Fork of the Carson River also has a low peak flow response and high base flow, so it is unclear why the slope of the peak flow is comparatively high for that basin in Figure12.

Base Flow

SMD and associated weather variables have been monitored in some alpine watersheds for almost a century. Hydroclimatology analyses have focused on the connection between climate and surface water. To the best of our knowledge, similar long-term observations of snowmelt-driven variations in shallow ground water have not been made. Nevertheless, observations of base flow 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 (Figure 13). These increases are also influenced by geology. Watersheds with a high mean soil thickness underlain by porous and permeable bedrock tend to have a relatively low maximum

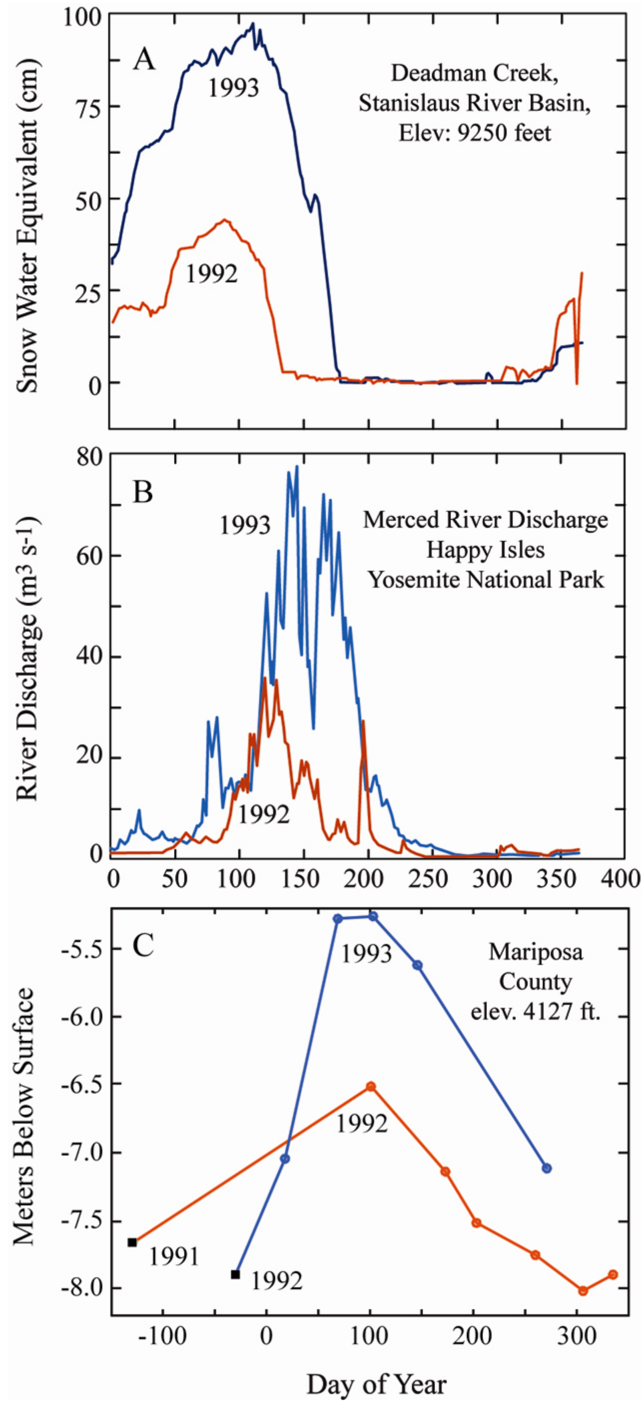

Figure 13. Comparison of snowpack (A), river discharge (B), and well water depth (C), in 1993, a wet year (blue) and 1992, a dry year. Well data (C) from USGS site number 373256119383001.The annual rise and decline in water level was about 2.5 meters in 1983, a year of high base flow throughout the Sierra Nevada.

peak flow, and a relatively high minimum or base flow, compared to watersheds with a low mean soil thickness underlain by impermeable granite. For example, the high-flow snowmelt discharge peaks are muted in the Cascade Mountain volcanic rock watersheds of Oregon (Tague and Grant 2004), compared to the granite-based watersheds of the Sierra Nevada.

Figure 14 is an example of differing responses to snowmelt with high flow variations, largely from climatic variations and base or low flow variations from geologic watershed differences in mean soil thickness and or bedrock permeability. The differing responses suggest the East Fork of the Carson watershed (approx 50% Tertiary Volcanic, 40% crystalline) has relatively more water storage, supporting a higher base flow than the Merced (about 80% crystalline, 15% Glacial till) watershed even though SMD runoff is much higher in the Merced.

The persistence in peak or high SMD in watersheds underlain by permeable granite as compared to watersheds with relatively impermeable granite (Figure 15) is also largely due to geologic influences. Hydrologic text books (c.f. Mount 1995) illustrate differences in infiltration for rain pulse responses in urban impermeable versus rural permeable watersheds (Figure 16, upper panel). A simple analogy to snowmelt discharge-driven watersheds shows that a watershed with a low base flow is more like the urban response, and a watershed with a high base flow is more like the rural response (Figure 16, lower panel).

The influence of antecedent wet or dry spells on base flow increases in watersheds from low to intermediate to high water storage (Figures 17–19). This effect is conceptually well known but a continuing subject of study.

In general, in watersheds with low base flow as a percentage of peak flow, the peak flow responds more to increasing mean annual snowmelt discharge than watersheds with a relatively high base flow as a percentage of peak flow (within a range of runoff). For example, the Merced River at Happy Isles has a low base flow as a percentage of peak flow (0.4 %), whereas the West Walker River has a relatively high base flow (2.1%). Subtracting the West Walker

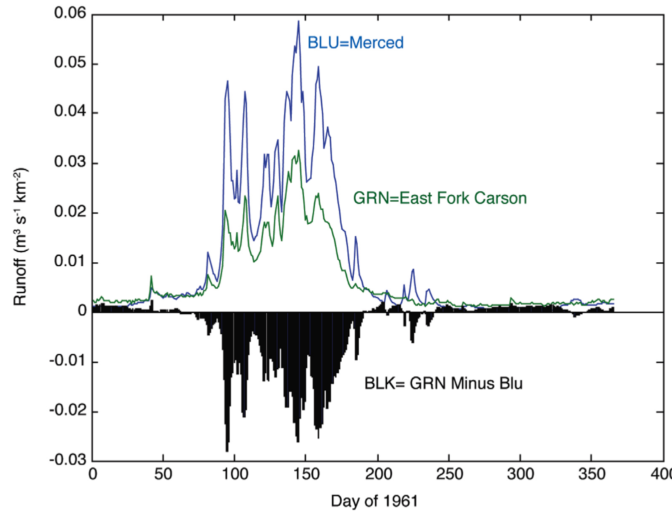

Figure 14. Mean daily river discharge for 1961: Merced River at Happy Isles (blue) and the East Fork of the Carson River (green) and the Carson minus Merced River discharge (black). Note that the high snowmelt-driven flow for the Merced River is almost twice that of the Carson River, but, for base flow, the Carson River is higher than the Merced River. Also note the fine scale correlations in mean daily river discharge during snowmelt as a result of the large-scale air temperature variations.

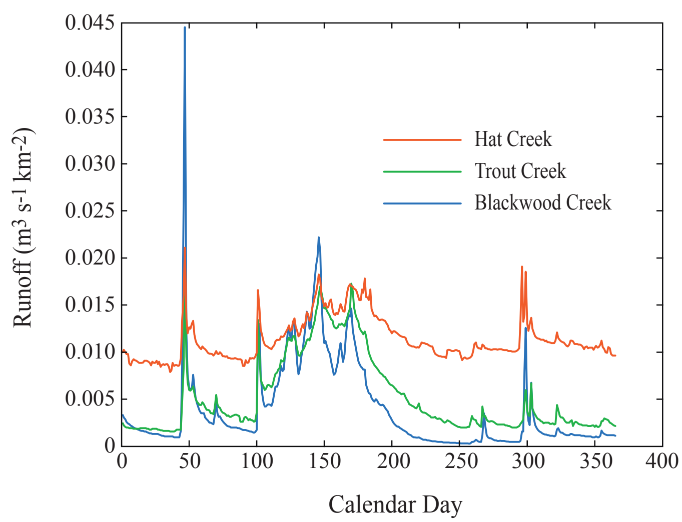

Figure 15. The maximum daily discharge in 1982 for creeks with differing rock composition: Hat Creek, permeable volcanic (red); Trout Creek, permeable unconsolidated sediments (green); and Blackwood Creek, impermeable Pliocene volcanic rock (blue). Note that besides the differences in base flow, the peak flow persists longer in the permeable- vs. impermeable-based watershed.

from the Merced peak flows with respect to increasing mean annual snowmelt discharge, results in a positive increase (Figure 20, C); whereas subtracting the West Walker from the Merced base flows with respect to increasing mean annual snowmelt discharge, results in the opposite: a negative decrease (Figure 20, D).

Mean snowmelt discharge (the horizontal axes of panels C and D in Figure 20) is used as an index of increasing annual snowmelt. Because of the strong spatial correlation in mean annual snowmelt discharge (Figure 4), using the West Walker River's mean annual snowmelt discharge instead of the Merced River's would make little difference. However, the correlations in panels C and D could be slightly refined by using the mean value of the two watersheds.

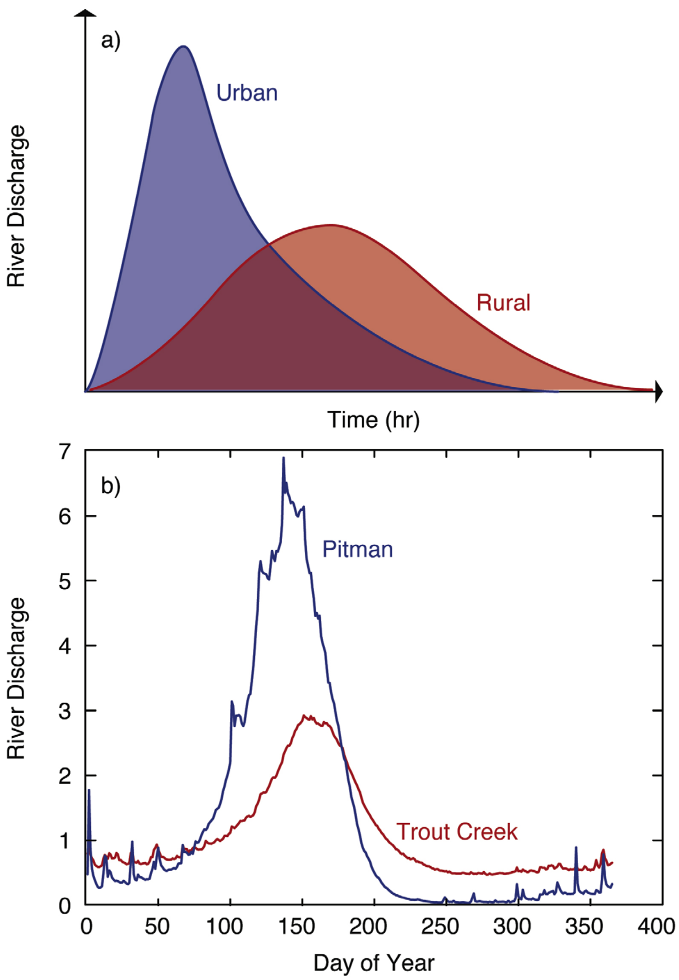

Figure 16. Upper panel: the difference in a rain impulse response for urban (impermeable) and rural (permeable) runoff (modified from Mount, 1995). Lower panel: the long-term mean annual hydrograph for the Pitman River (base flow is 0.12% peak flow) and Trout Creek (base flow Is 9.5% of peak flow). Note the difference in the two panels: the upper panel illustrates an impulse (short term) rain response and the lower panel a step (longer term) snowmelt response.

When the Merced River peak and base flow increases with respect to increasing Merced River mean annual snowmelt discharge are subtracted from the corresponding peak and base flow responses of the other 23 gage observations, the Merced River has a lesser peak and a greater base flow response than the gages designated by dark blue dots (largely in the upper left quadrant of Figure 21). The Merced River response is then similar to the West Walker River in the Figure 20 comparison (high base flow). However, when the Merced River has a greater peak and lesser base flow response than the gages designated by dark red dots (largely in the lower right quadrant of Figure 21; also see Table 6 for plot statistics and Appendix C, http://sfbay.wr.usgs.gov/hydroclimate/alpine/Sierra.html), the Merced River (high peak flow) response is the same relation as in the West Walker River as in the Figure 20 comparison (high base flow).

Further, fisheries scientists know what makes a good habitat for trout (cf. Moyle 2002), and that includes high base flow. Therefore, streams with good fishing were added to the work-in-progress watershed classification, assuming that if a watershed with a high base flow were also known for good fishing, some of the other characteristics of a good habitat for fish might be present. Perhaps the watersheds that appear to fall within the good fishing group, but have not been identified with good fishing (noted with an asterisk in Figure 22), do not meet a sufficient number of watershed and stream good habitat qualities.

PREDICTION

The amplitude of peak and base flow correlate with initial SWE, however, the timing correlation is only strong for Bear and Sagehen Creeks (Appendix D, http://sfbay.wr.usgs.gov/hydroclimate/alpine/Sierra.html). The correlation between peak flow amplitude

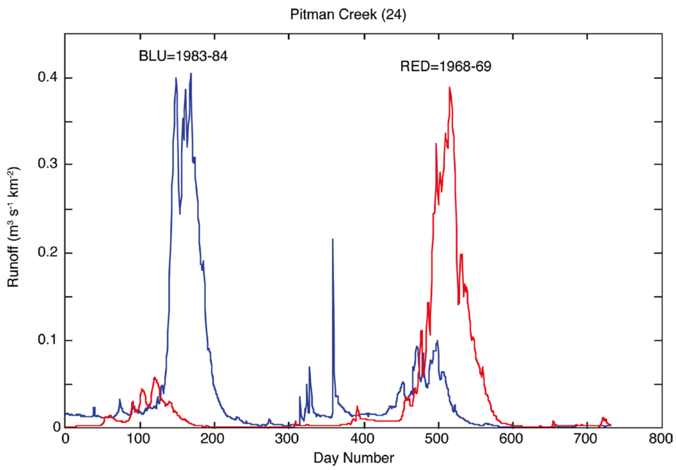

Figure 17. Lower base flow watershed (Pitman Creek) with a wet year annual hydrograph (red) preceded by a dry year (red) and a dry year annual hydrograph (blue) proceeded by a wet year (blue). Note that base flow is similar in 1969 and 1984, and in 1968 and 1983.

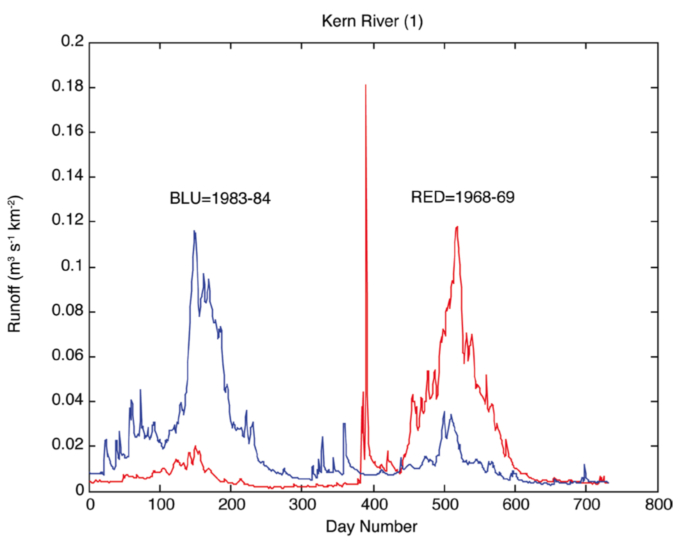

Figure 18. Moderate base flow watershed (Kern River at Kernville) with a wet year annual hydrograph (red) preceded by a dry year (red), and a dry year annual hydrograph (blue) proceeded by a wet year (blue). Note that base flow is similar in 1969 (wet) and 1984 (dry), but lower in 1968 (dry) than 1983 (wet).

and initial SWE can be used to predict peak flow weeks in advance because the initial SWE observation is made near April 1, and peak flow typically occurs two months later, in early June (Figure 23, and Peterson et al. 2002). Results in Appendix D (http://sfbay.wr.usgs.gov/hydroclimate/alpine/Sierra.html) also show base flow amplitude can be predicted four months or more in advance, based on initial SWE.

SUMMARY AND EARLY IMPLICATIONS

A long term data-set of hydrologic measurements at 24 gage locations in 18 watersheds in the Sierra Nevada was investigated to define variations in snowmelt-driven stream discharge responses to climatic and spatial geologic variations. The approach started with hydrologic responses to climatic variations because: 1) climatic variations are the largest source of variability in mountain snowmelt-driven river discharge; 2) the annual hydrograph starts with strong climatic-derived responses—the spring

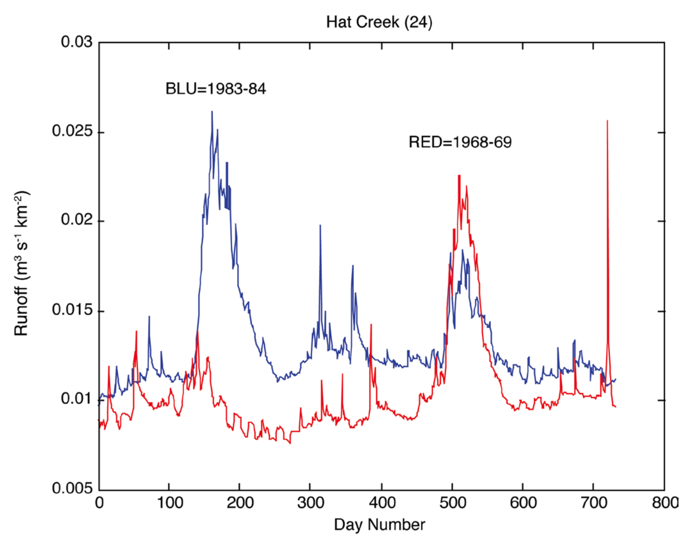

Figure 19. High base flow watershed (Hat Creek) with a wet year hydrograph (red) proceeded by a dry year (red), and a dry year hydrograph (blue) proceeded by a wet year (blue). Note that the base flow did not fully recover in the wet year (1969, presumably due to a large loss in water storage in the proceeding dry year (1968). The dry year (1984) hydrograph, however, appears to be supported by the preceding wet year (1983), and perhaps the summer-fall rain.

Table 6 . INTRA BASIN PEAK AND BASE FLOW STATISTICS INCLUDING THE LONG-TERM MEAN (CUBIC METERS PER SECOND)

Watershed		Peak Flow		Base Flow			Correlation Between Peak and Base Flow
		(Mean)	*(Std)*	*(Mean)*	*(Std)*	*(as a % of Qmax)*	
1	Kern at Kernville	98.1	72.2	5.0	2.5	5.1%	R=0.92
2	Combined Kern	94.1	60.9	5.1	2.1	5.4%	R=0.88
3	North Fork Tule	66	6.9	0.35	0.13	1.3%	R=0.57
4	Middle Fork Kaweah	23.6	16.2	0.46	0.24	2.0%	R=0.72
5	Marble Fork Kaweah	16.7	10.9	0.15	0.11	0.90%	R=0.71
6	Pitman Creek	11.1	8.4	0.013	0.019	0.12%	R=0.56
7	Bear Creek	17.3	7.2	0.20	0.14	0.81%	R=0.45
8	San Joaquin at Millers Crossing	100.8	47.1	1.6	0.83	1.6%	R=0.75
9	Merced at Happy Isles	67.7	27.8	0.27	0.25	0.40%	R=0.56
10	Merced at Pohono	116.5	54.2	0.69	0.40	0.59%	R=0.71
11	Middle Fork Tuolumne	14.2	10.4	0.055	0.069	0.39%	R=0.77
12	Stanislaus at Clark Fork	23.4	10.2	0.67	0.27	2.9%	R=0.77
13	Highland Creek	25.4	14.7	.047	.052	0.19%	R=0.42
14	West Walker	46.2	20.0	0.95	0.46	2.1%	R=0.65
15	West Walker near Coleville	45.8	20.1	1.2	0.58	2.6%	R=0.66
16	Cole Creek	15.7	9.5	0.0022	0.006	0.014%	R=0.04
17	East Fork Carson	59.6	40.9	1.4	0.73	2.4%	R=0.81
18	West Fork Carson	17.0	9.9	0.48	0.21	2.8%	R=0.82
19	Trout Creek	3.8	2.4	0.36	0.21	9.5%	R=0.89
20	Blackwood Creek	6.8	3.6	0.053	0.026	0.87%	R=0.63
21	Carson near Fort Churchill	25.4	14.7	0.22	0.052	0.19%	R=0.72
22	South Yuba	38.8	16.7	0.23	0.14	0.59%	R=0.26
23	Sagehen Creek	2.2	1.6	0.066	0.028	3.0%	R=0.68
24	Hat Creek	7.0	2.0	3.5	0.60	50%	R=0.66

pulse and peak flow—and ends with a spatial geologic-derived response: base flow; 3) the climatic air temperature variations are large-scale, and air temperature and snowmelt river discharge variations strongly correlate; therefore, mountain snowmelt river discharge variations are large-scale (the spatial geologic variations are not large-scale). Thus, inter-basin correlations in mean annual snowmelt river discharge, peak flow, and—to a lesser extent—base flow are strong (in magnitude). Intra-basin correlations in mean annual snowmelt river discharge, peak flow and base flow depend on a number of physical characteristics that require further investigation. Trends towards an earlier spring, such as the earlier timing of the spring pulse and center of mass, have been well established for the western U.S., including the Sierra Nevada basins. Trends towards earlier peak flows have been mostly studied though numerical simulation. Observationally-based study also shows earlier peak flow. When base flow is plotted against peak flow (Appendix E, http://sfbay.wr.usgs.gov/hydroclimate/alpine/Sierra.html), the correlation is

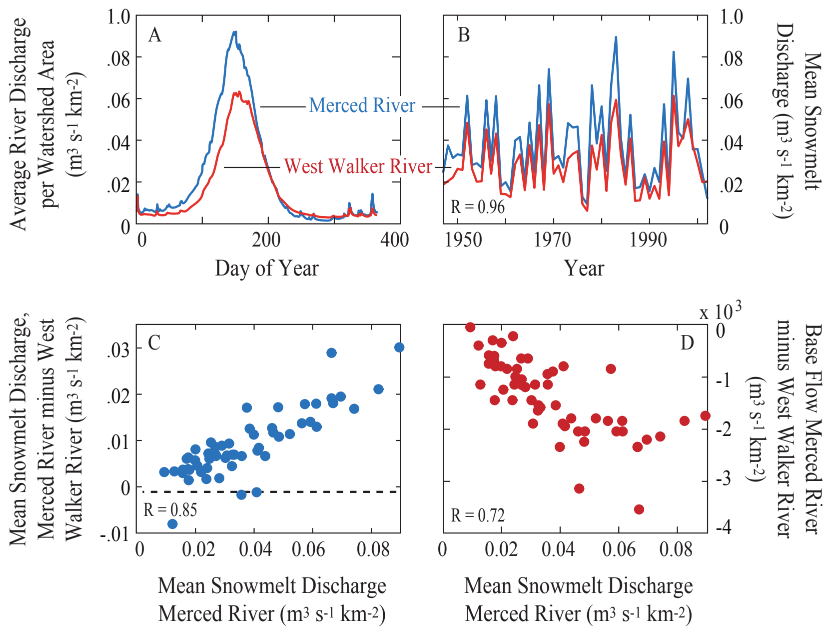

Figure 20. (A) Long-term mean discharge for the Merced River at Happy Isles (blue) and the West Walker River (red); (B) the Merced River (blue) and the West Walker River (red) mean annual snowmelt river discharge 1947-2002 (averaged over days 105-275 to minimize rain contamination); (C) the Merced River minus the West Walker River peak flow with respect to Merced River mean annual snowmelt river discharge per watershed area; (D) the Merced River minus the West Walker River annual base (low) flow with respect to the Merced River mean annual snowmelt river discharge per watershed area. Note the reversal in the panels C and D correlations.

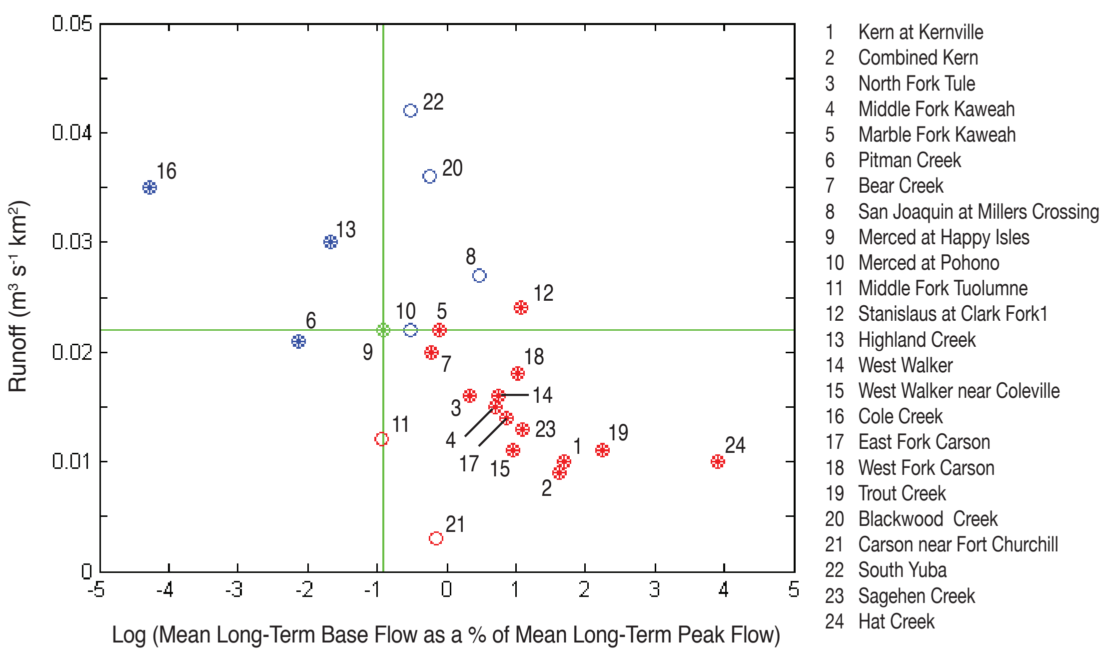

Figure 21. Watershed mean run off (specific runoff) with respect to the log (to the base e) of mean base flow as a percentage of mean peak flow. The dots in the Figure are for the 24 gages; the green dot in the crosshairs is the Merced River at Happy Isles. Red dots represent streams that have a lesser peak and greater base flow than the Merced River. The blue dots stand for streams with higher peak and lesser base flow than the Merced. The open dots represent values that are exceptions largely due to high or low runoff.

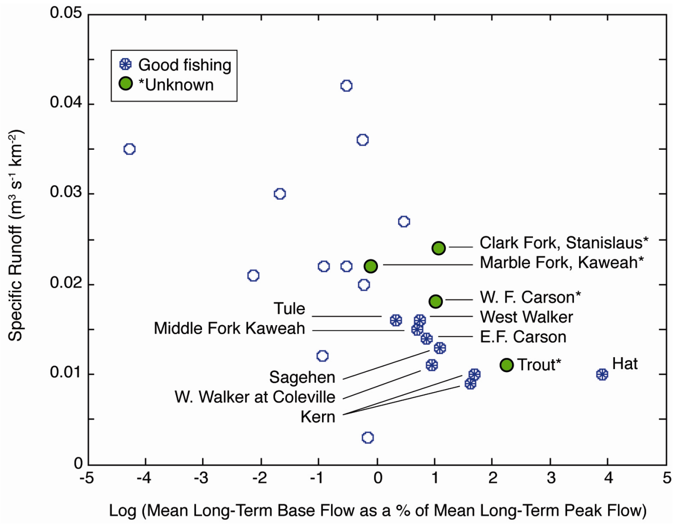

Figure 22. Mean runoff versus the log of mean base flow as a % of mean peak flow for the watersheds in this study. The streams or major reaches of streams with good trout fishing are dark blue; the fishing quality in watersheds with a star has not yet been determined. Good fishing is based on a cursory survey of staff members from the California Department of Fish and Game, the U.S. Department of Fish and Wildlife, trout fishing websites, and the U.S. Biological Research Division.

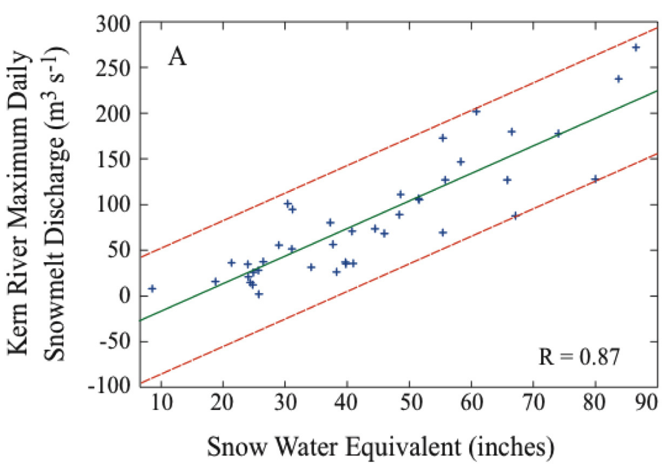

Figure 23. An example correlation of annual maximum daily snowmelt discharge amplitude with annual initial snow water equivalent, Kern River at Kernville. The red lines are plus and minus two standard deviations from the correlation.

stronger than when base flow is plotted against SWE (Appendix D, http://sfbay.wr.usgs.gov/hydroclimate/alpine/Sierra.html). In future work, a scheme could be made that predicts base flow once peak flow is known (approximately in late May–early June). By combining the resulting base flow prediction with the inverse of the discharge rating curve (water depth as a function of discharge), minimum water depth in fall could also be predicted months in advance.

Watershed differences in climatic responses are made discernable by the addition of spatial variations in geologic factors. Inferred mean soil thickness and bedrock permeability were shown to influence snowmelt flow pathways. Surface water flows increased more in response to increasing snowmelt in watersheds with relatively impermeable bedrock and low mean soil thickness than in watersheds with permeable bedrock with a high mean soil thickness, and with the opposite relation for base flow (here assumed to represent the contribution of shallow ground water). Base flow increased more in response to increasing snowmelt in watersheds with a high mean soil thickness and permeable bed rock, presumably resulting in greater storage capacities.

In essence, many of the results and interpretations in this initial study are consistent with, and captured by, a work-in-progress Sierra Nevada snowmelt-driven watershed classification, mean runoff versus log (mean base flow as a percent of mean peak flow), Figure 21. The classification predicts differences in watershed responses to peak and base flow with increasing mean annual snowmelt-driven river discharge. High base flow implies the watershed has high water storage. Necessary future work includes adding to the classification as many Sierra Nevada watersheds with river gages as possible, past and present, and quantifying more properties (including mean precipitation and soil thickness) and how increasing soil water storage increases the importance of antecedent precipitation.

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