Sierra Nevada Hydroclimatology: An Experimental Prediction of Maximum Daily Snowmelt Discharge in 2005

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ABSTRACT

An unusually wet winter and cool spring provided above average levels of initial snow water equivalent in the Sierra Nevada in 2005. The snow water anomalies increased from north to south as did the magnitude of the predicted maximum daily snowmelt discharge for the 24 stream gage locations. The north to south variation in maximum daily snow melt discharge was from 110% to 200% of the mean. The day of maximum daily snowmelt discharge forecast also increased from north to south from 2 to 10 days longer than the mean. In general, the initial snow water equivalent versus maximum daily snow melt discharge correlations were greater than R= 0.75, and the day of the maximum daily snow melt discharge versus initial snow water equivalent were less than R=0.4. Future work includes a different statistical method in defining the correlation between maximum daily snowmelt discharge and initial snow water equivalent in alpine watersheds.

INTRODUCTION

Fresh water is the most important natural resource in California, and climate is the most important source of variability in that resource. Thus, information on the variations in snowpack and snowpack-driven river discharge in the Sierra Nevada is essential in making water management decisions and in climate variability and change research.

In a simplified description, the snowmelt discharge (SMD) annual cycle has three stages: *1)* an early spring SMD pulse (Cayan, et. al., 2004); *2)* a late spring-early summer maximum SMD; and *3)* a fall low river discharge or base flow (*Fig. 1*). In this seasonal context, the timing and magnitude of the early spring SMD pulse varies more with air temperature and solar insolation (a warm or cool spring) than maximum SMD, and maximum SMD varies more with initial snowpack (a wet or dry winter), than the spring pulse (Lundquist, et. al., 2004, Peterson, et. al., 2004). Base flow varies with watershed soil and rock permeability (Tague and Grant, 2004), and all of the above (Peterson, 2005, Constantz, 1998).

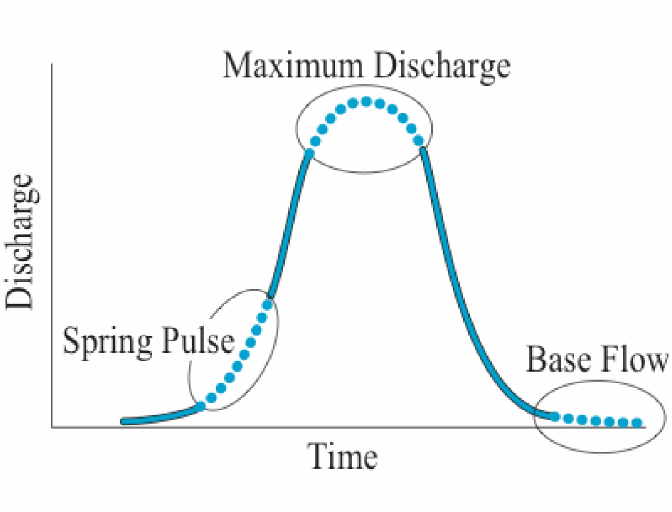

Figure 1: Schematic illustration of three major features of the snowmelt discharge hydrograph.

The historical maximum in daily snow melt discharge (MDSMD) in stage 2, correlates with the initial snow water equivalent (swe) observed near April 1. Because the timing of MDSMD is near June 1, MDSM can be predicted weeks or months in advance of the April 1 swe observation. This study is an extension of earlier work on characterizing snowmelt discharge at the same 24 gages in the Sierra Nevada (Peterson, et. al., 2005). Also, previous 2000, 2001 and 2002 MDSMD forecasts were made for a small number, but broadly located, alpine watersheds (Peterson, et. al., 2000, 2001, and 2002). The following gives the data, methods, and the forecast results for MDSMD in 2005. This is followed by a discussion of some of the findings, problems, and improvements in making such forecasts.

DATA AND METHODS

MDSMD is predicted for 24 snow-fed river discharge locations based on initial swe observations at 18 snow pack monitoring locations in the Sierra Nevada (*Fig. 2*, Tables 1 and 2).

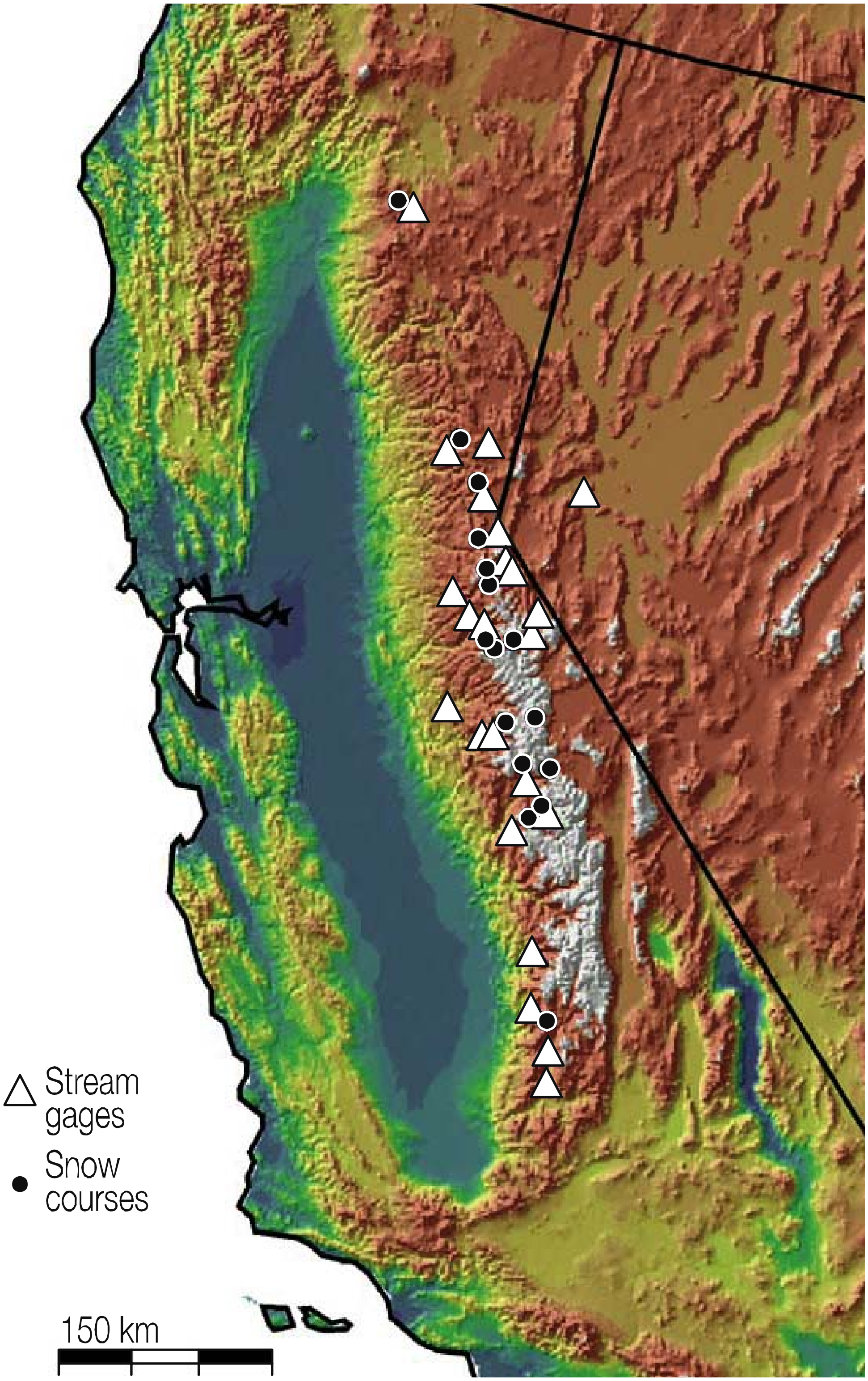

Figure 2: Stream gage and snow course locations.

TABLE 1

River	USGS Number	Gage Elevation (meters)	Area (km2)	Years
Kern at Kernville	11186000	1,103	2,613	1912 - present
Combined Kern	11186001		2,191	1961 - present
North Fork Tule	11202001	890	101.8	1940 - present
Middle Fork Kaweah	11206501	640	264.2	1949 - present
Marble Fork Kaweah	11208001	655	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 Crossing[1]	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
Stanislaus at Clark Fork[1]	11292500	1,679	174.8	1950 - 1994
Highland creek[2]	11294000	1,932	119.1	1952 - present
West Walker	10296000	2,009	468.9	1938 - present
West Walker near Coleville	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 Yuba[1]	11414000	1,683	134.2	1942 -1994
Sagehen Creek	10343500	1,926	27.2	1953 - present
Hat Creek[1]	11355500	1,311	419.6	1930 - 1994

[1/] Discontinued.

[2/] Record altered from 1981 to present.

TABLE 2

River Basin	Snow Station		Elevation (Meters)	Start of Record
Kern at Kernville	205	Mammoth Pass	2800	3/1928
Combined Kern	205	Mammoth Pass	2800	3/1928
North Fork Tule	247	Quaking Aspen	2100	4/1937
Middle Fork Kaweah	243	Panther Meadow	2600	3/1925
Marble Fork Kaweah	243	Panther Meadow	2600	3/1925
Pitman Creek	190	Kaiser Pass	2800	4/1930
Bear Creek	324	Lake Thomas Edison	2400	2/1958
San Joaquin at Millers Crossing[1]	193	Cora Lakes	2600	4/1939
Merced at Happy Isles	176	Snow Flat	2700	2/1930
Merced at Pohono	176	Snow Flat	2700	2/1930
Middle Fork Tuolumne	157	Dana Meadows	3000	1/1926
Stanislaus at Clark Fork[1]	138	Lower Relief Valley	2500	5/1930
Highland Creek[2]	140	Eagle Meadow	2300	3/1931
West Walker[2]	152	Sonora Pass	2700	4/1930
West Walker near Colville	152	Sonora Pass	2700	4/1930
Cole Creek	129	Blue Lakes	2400	4/1918
East Fork Carson	106	Upper Carson Pass	2600	1/1930
West Fork Carson	106	Upper Carson Pass	2600	1/1930
Trout Creek	96	Lake Lucille	2500	4/1916
Blackwood Creek	318	Squaw Valley	2300	3/1954
Carson near Fort Churchill	106	Upper Carson Pass	2600	1/1930
South Yuba[1]	66	Meadow Lake	2200	4/1920
Sagehen Creek	318	Squaw Valley	2300	3/1954
Hat Creek[1]	33	Thousand Lakes	2000	3/1946

[1/] Discontinued.
[2/] Record altered from 1981 to present.

The 24 U.S. Geological river gages in this study are the same as the California river gage locations in Stewart et al. (2004, 2005) from the Hydroclimate Data Network. The swe observations are from the California Data Exchange Center web site and were mostly from a high elevation in the same or in a nearby watershed.

The time period for determining maximum daily snowmelt discharge amplitude and timing was limited from April 20 to August 13 (calendar days 110-225), to minimize early in the year and late in the year rain-caused river discharge peaks. The initial snow pack swe was observed near April 1. Correlation statistics of MDSMD amplitude and timing as a function of swe were calculated using standard methods. In essence, a historical time series of swe, MDSMD, and the initial swe for 2005, were all that were needed to estimate the linear coefficients, M and b, and to predict the 2005 MDSMD magnitude and timing in the equation:

$$\mathrm{MDSMD}(2005) = M * \mathrm{swe}(2005) + b \qquad (1)$$

RESULTS

The 2005 magnitude of maximum daily snowmelt discharge is predicted to increase along the Sierra Nevada from north to south and to be 110% to 200% of the long-term mean. As a result, the north to south predicted timing is slightly later in the season, from two to seven days later than the mean. This is consistent with the observed increase in precipitation from north to south during winter and early spring, a reversal of the mean pattern.

The correlation in long-term MDSMD magnitude with initial swe is greater than 0.75 and the correlation in timing is less than 0.4. The mean swe, MDSMD, day of MDSMD, and correlation coefficients for the MDSMD amplitude and day of MDSMD vs. swe for the 24 gage locations, are in Table 3. Typical examples of the correlations are in *Fig. 3, (a)* and *(b).*

TABLE 3

River Station Name	**Calendar Years**	**Mean initial snowpack (inches)**	**Mean MDSMD (m^3s^{-1})**	**Correlation MDSMD vs. initial snowpack**	**Mean Day of MDSMD**	**Correlation Day of MDSMD vs. initial snowpack**
Kern at Kernville	1954-1993	42.1	93.3	0.89	147	0.26
Combined Kern	1947-2001	42.6	93	0.88	146	0.37
North Fork Tule	1947-2001	12.1	5.82	0.42	132	0.25
Middle Fork Kaweah	1950-2001	36.3	22.5	0.82	144	0.33
Marble Fork Kaweah	1951-2001	36.3	16.0	0.80	144	0.36
Pitman Creek	1947-2001	37.6	10.7	0.68	134	0.43
Bear Creek	1958-2001	15.4	18.3	0.75	162	0.36
San Joaquin at Millers Crossing[1]	1952-1991	35.3	98.5	0.85	148	0.43
Merced at Happy Isles	1947-2002	43.8	76.5	0.76	147	0.29
Merced at Pohono	1947-2002	43.8	113	0.77	142	0.29
Middle Fork Tuolumne	1950-1997	30.0	14.1	0.78	136	0.22
Stanislaus at Clark Fork[1]	1952-1994	38.1	23.1	0.87	148	0.32
Highland Creek[2]	1954-1988	23.4	23.4	0.81	137	0.27
West Walker[2]	1947-2002	24.7	46.2	0.79	152	0.48
West Walker near Colville	1947-2002	24.9	46.2	0.83	152	0.45
Cole Creek	1947-2001	35.3	14.8	0.65	136	0.34
East Fork Carson	1961-2002	35.3	57	0.73	142	0.27
West Fork Carson	1947-2002	35.4	16.8	0.79	133	0.39
Trout Creek	1961-2001	58.9	3.8	0.85	150	0.53
Blackwood Creek	1961- 2002	48	6.8	0.79	139	0.37
Carson near Fort Churchill	1947-1999	36	55.7	0.84	143	0.26
South Yuba[1]	1949-1993	54.9	37.6	0.58	136	0.39
Sagehen Creek	1954-2001	48.4	2.2	0.74	126	0.62
Hat Creek[1]	1949-1993	33.9	7.0	0.65	148	0.65

[1/] Discontinued

[2/] Record altered 1989 to present.

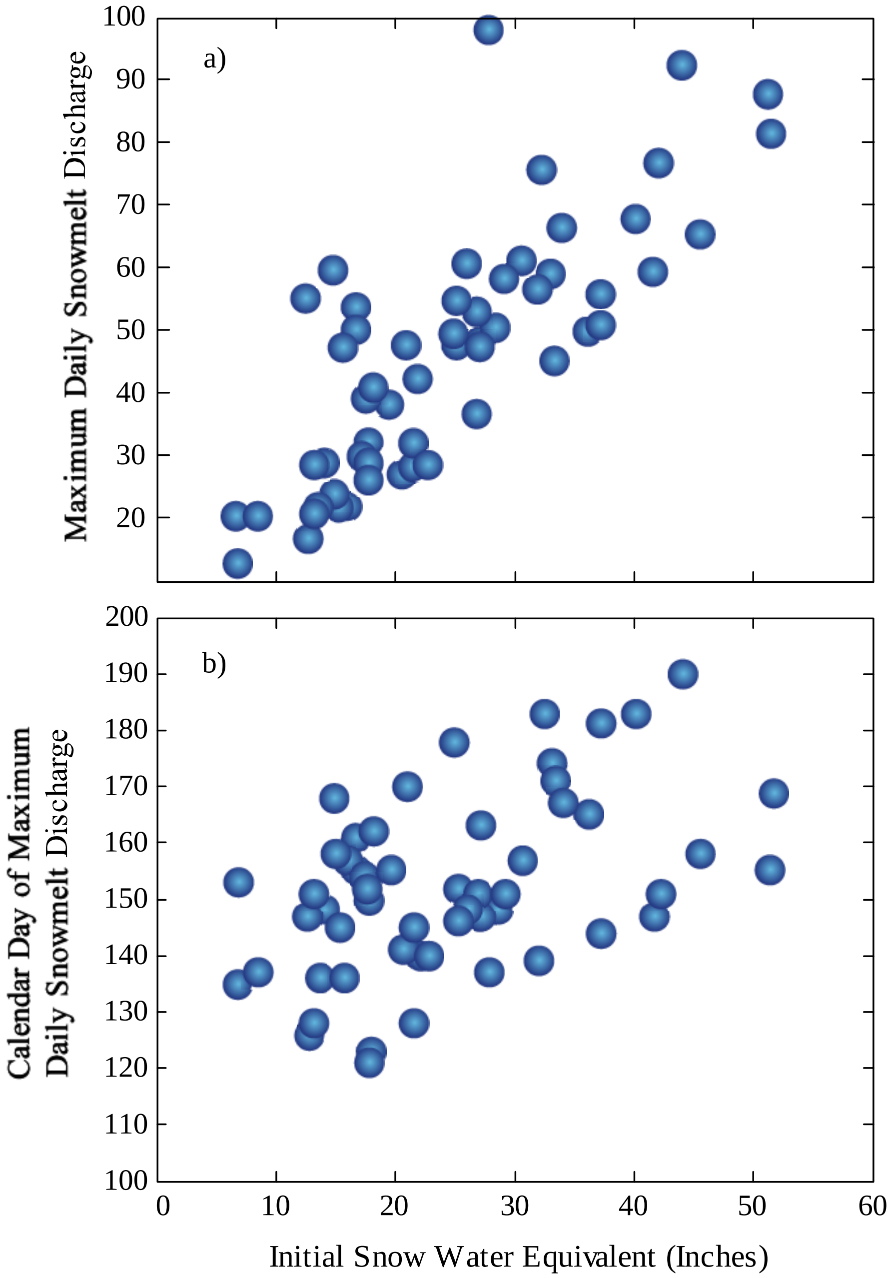

Figure 3: a) the correlation in amplitude of MDSMD, West Walker River, with initial swe; b) the correlation in timing of the day of MDSMD with swe from Sonora Pass, 1947 to 2002.

The MDSMD 2005 forecast is in Table 4. To illustrate a source of error in timing, *Figs. 4* and *5* show a large upstream/downstream difference in timing, but not in amplitude, for the West Walker River, 1981 and in the full time series (*Fig. 6*). Also, although MDSMD timing in the West Walker is 11 days earlier in 2002 than in 1947, MDSMD amplitude increases slightly over the same period (*Fig.7*). That is, the long-term trend towards earlier timing in MDSMD was not reversed by the weak long-term trend in increasing MDSMD (increasing MDSMD would cause the MDSMD timing to be longer). An interesting difference in snowmelt versus rain is also shown. A rain-caused difference in upstream/downstream river discharge was not observed for a similar magnitude in snow melt discharge (*Fig. 8*, *a*, *b*, *c* and *d* and *Fig. 9*).

TABLE 4

River Station Name	SWE inches (% of mean)	MDSMD REGRESSION M (swe)+b	MDSMD PREDICTION m^3 s^{-1} (% of mean)	TIMING REGRESSION M (swe)+b	TIMING PREDICTION Calendar Day (+ day)
Kern at Kernville	68.5 (163)	3.34(swe)-44.2	184 (197)	0.20(swe)+138	153 (6)
Combined Kern	68.5 (161)	2.96(swe)-33.0	170 (183)	0.302(swe)+134	154 (8)
North Fork Tule	20 (165)	0.158(swe)+3.92	7.08(122)	0.247(swe)+129	134 (2)
Middle Fork Kaweah	54 (149)	0.521(swe)+3.57	32(142)	0.363(swe)+131	151 (7)
Marble Fork Kaweah	54 (149)	0.401(swe)+1.45	23(144)	0.399(swe)+129	151 (7)
Pitman Creek	58 (154)	0.317(swe)-1.26	17(159)	0.317(swe)+122	141 (7)
Bear Creek	27.6 (179)	0.611(swe)+8.89	26(142)	0.777(swe)+150	171 (9)
San Joaquin at Millers Crossing[1]	62.5 (177)	2.04(swe)+26.5	154(156)	0.395(swe)+134	159 (11)
Merced at Happy Isles	54.5 (124)	1.14(swe)+17.5	80(104)	0.251(swe)+135	150 (3)
Merced at Pohono	54.5 (124)	2.17(swe)+17.9	136(120)	0.20(swe)+133	144 (2)
Middle Fork Tuolumne	40.3 (134)	0.587(swe)-3.55	20(142)	0.20(swe)+130	138 (2)
Stanislaus at Clark Fork[1]	60.1 (158)	0.521(swe)+3.91	35(152)	0.27(swe)+138	154 (6)
Highland Creek[2]	39 (167)	0.705(swe)+6.48	34(145)	0.193(swe)+132	140 (3)
West Walker[2]	36.4 (147)	1.44(swe)+10.6	63(136)	0.681(swe)+135	160 (8)
West Walker near Colville	36.4 (146)	1.53(swe)+7.64	63(136)	0.60(swe)+137	159 (7)
Cole Creek	46 (130)	0.388(swe)+1.17	19(128)	0.307(swe)+125	139 (3)
East Fork Carson	46 (130)	1.71(swe)-3.32	75(132)	.241(swe)+133	144 (2)
West Fork Carson	46 (130)	0.529(swe)-1.92	22(131)	0.323(swe)+122	137 (4)
Trout Creek	62.9 (107)	0.0928(swe)-1.72	4.2(110)	0.41(swe)+126	152 (2)
Blackwood Creek	52.8 (110)	0.147(swe)-0.285	7.5(110)	0.30(swe)+124	140 (1)
Carson near Fort Churchill	46 (128)	2.01(swe)-16.5	76(134)	0.252(swe)+134	146 (3)
South Yuba[1]	61.3 (112)	0.414(swe)+14.9	40(106)	0.28(swe)+121	138 (2)
Sagehen Creek	52.8 (109)	.0648(swe)-0.984	2.4(109)	.0427(swe)+106	128 (2)
Hat Creek[1]	32.6 (96)	0.0892(swe)+4.0	6.9(99)	0.203(swe)+141	148 (0)

[1/] Discontinued.

[2/] Record altered 1989 to present.

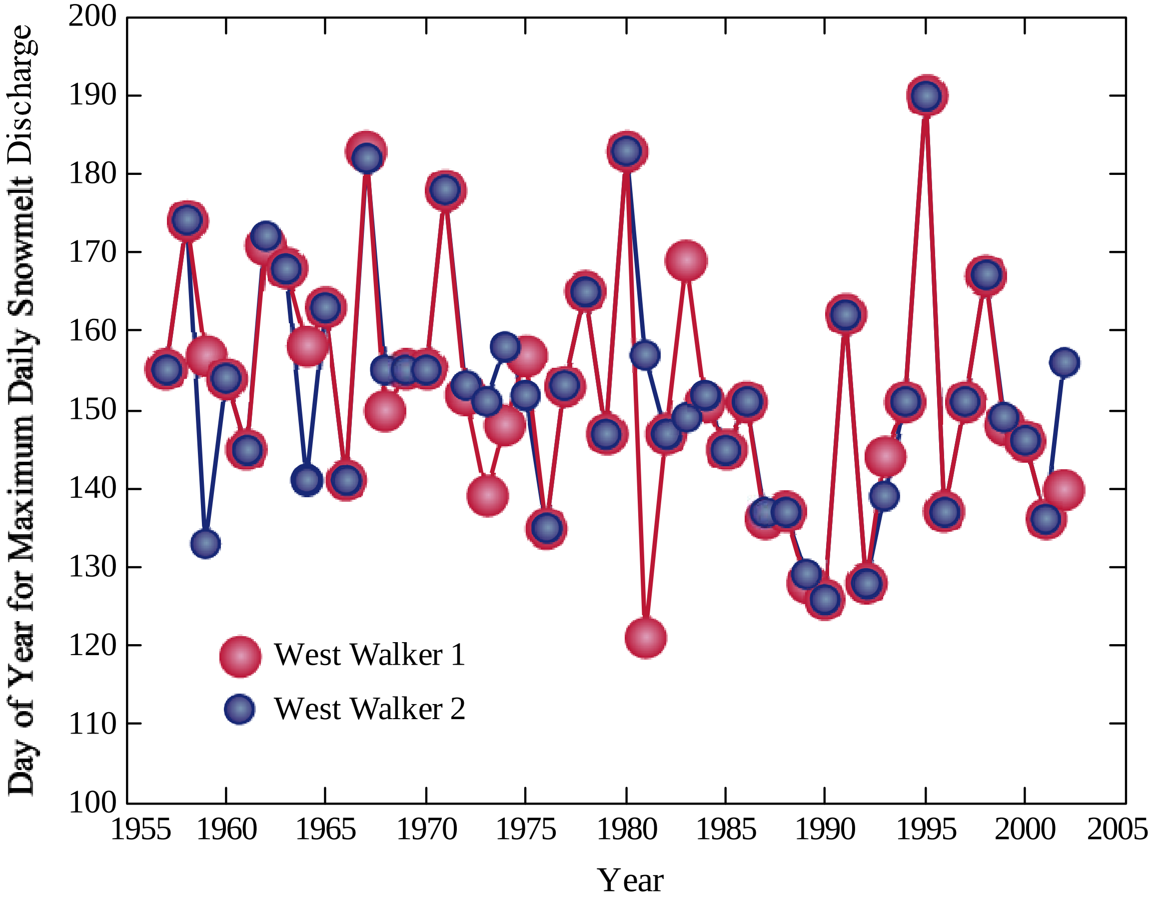

Figure 4: The long term variations in day of MDSMD in upper (red) and lower (blue) West Walker River. Note the 1981 large difference in upper and lower watershed timing of MDSMD due to the small difference in peak magnitude.

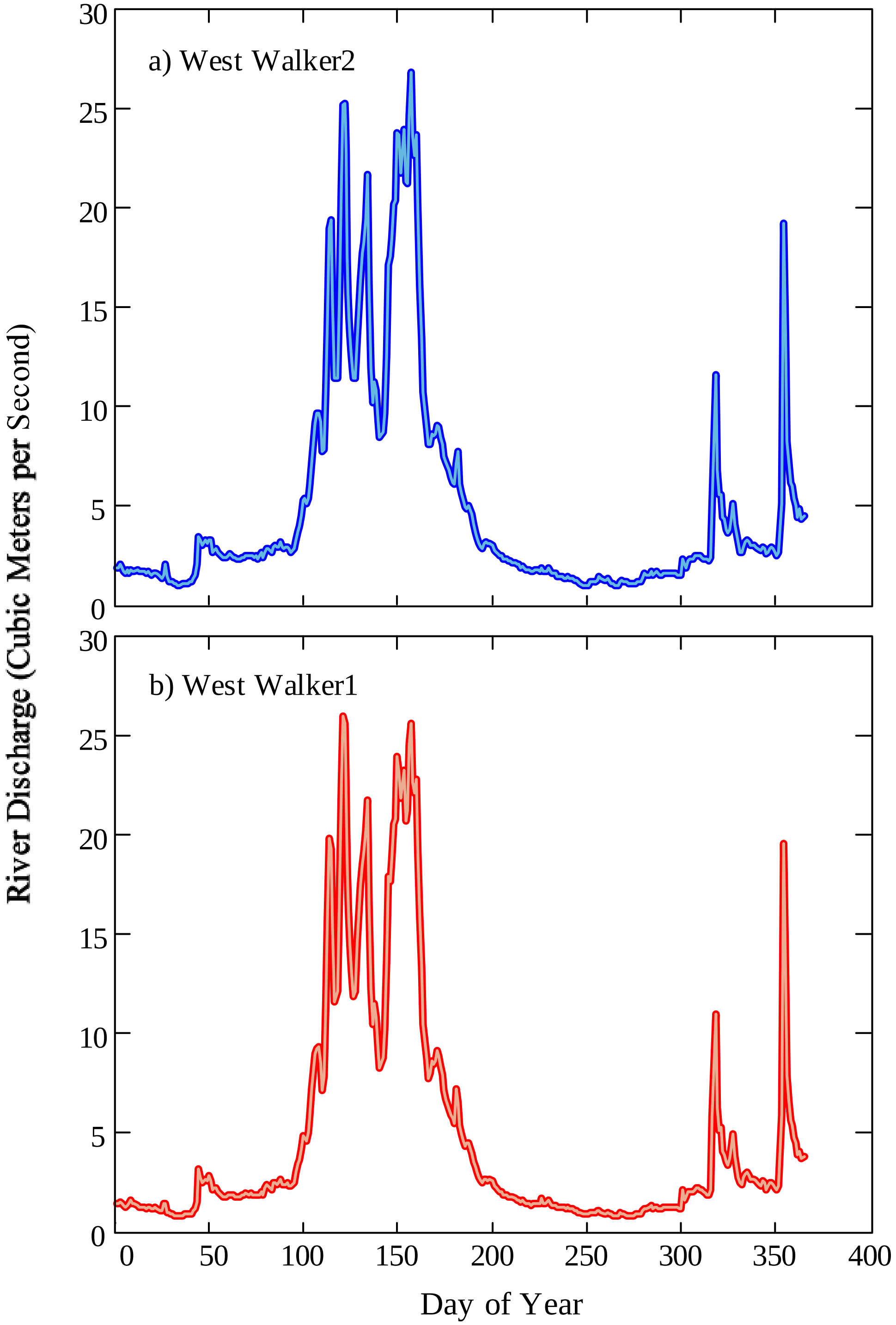

Figure 5: a) the upper daily West Walker River discharge; b) the lower daily West Walker River discharge.

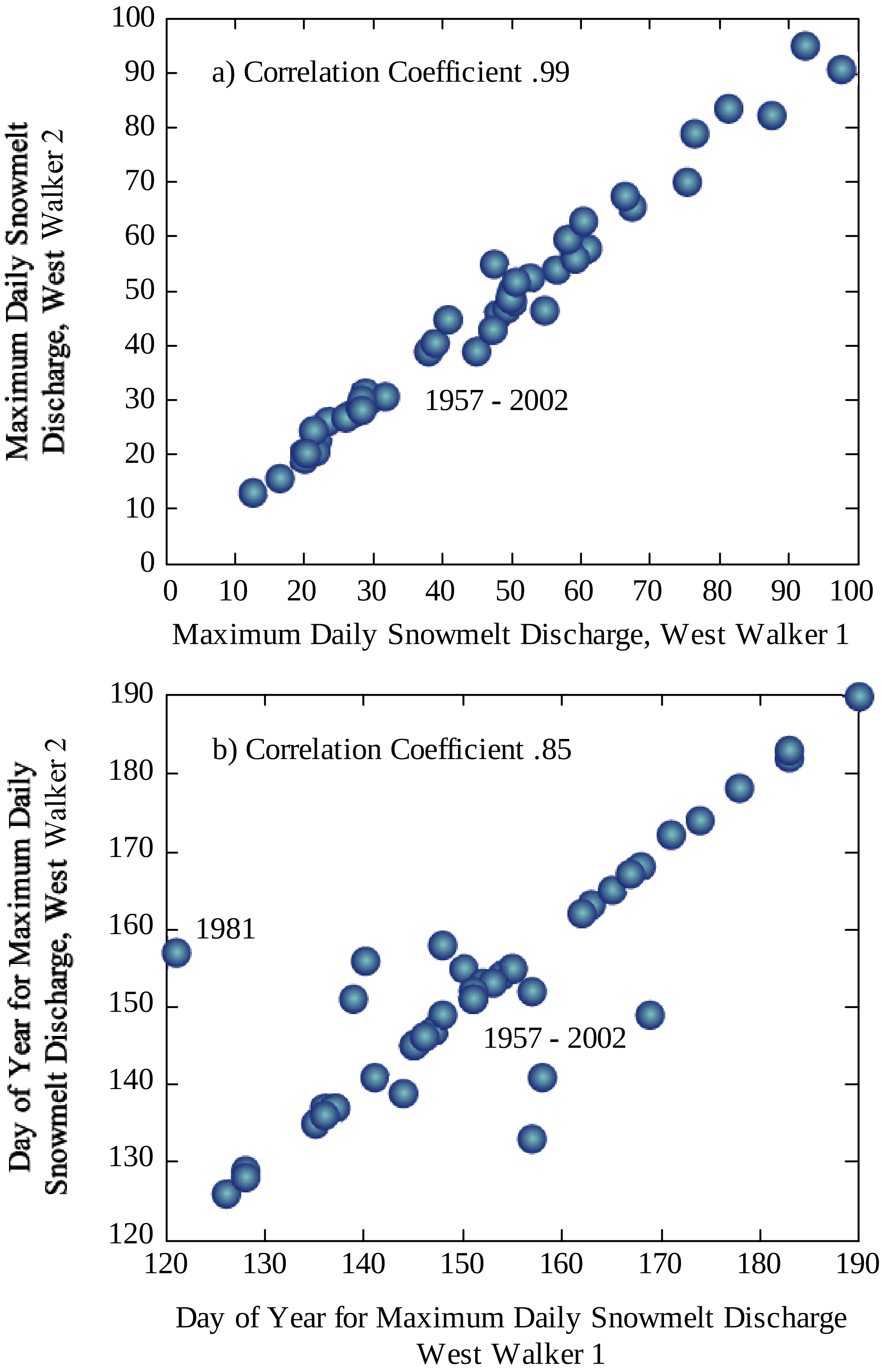

Figure 6: a) the upper/lower correlation in MDSMD amplitude; b) the same as (a), but for the timing.

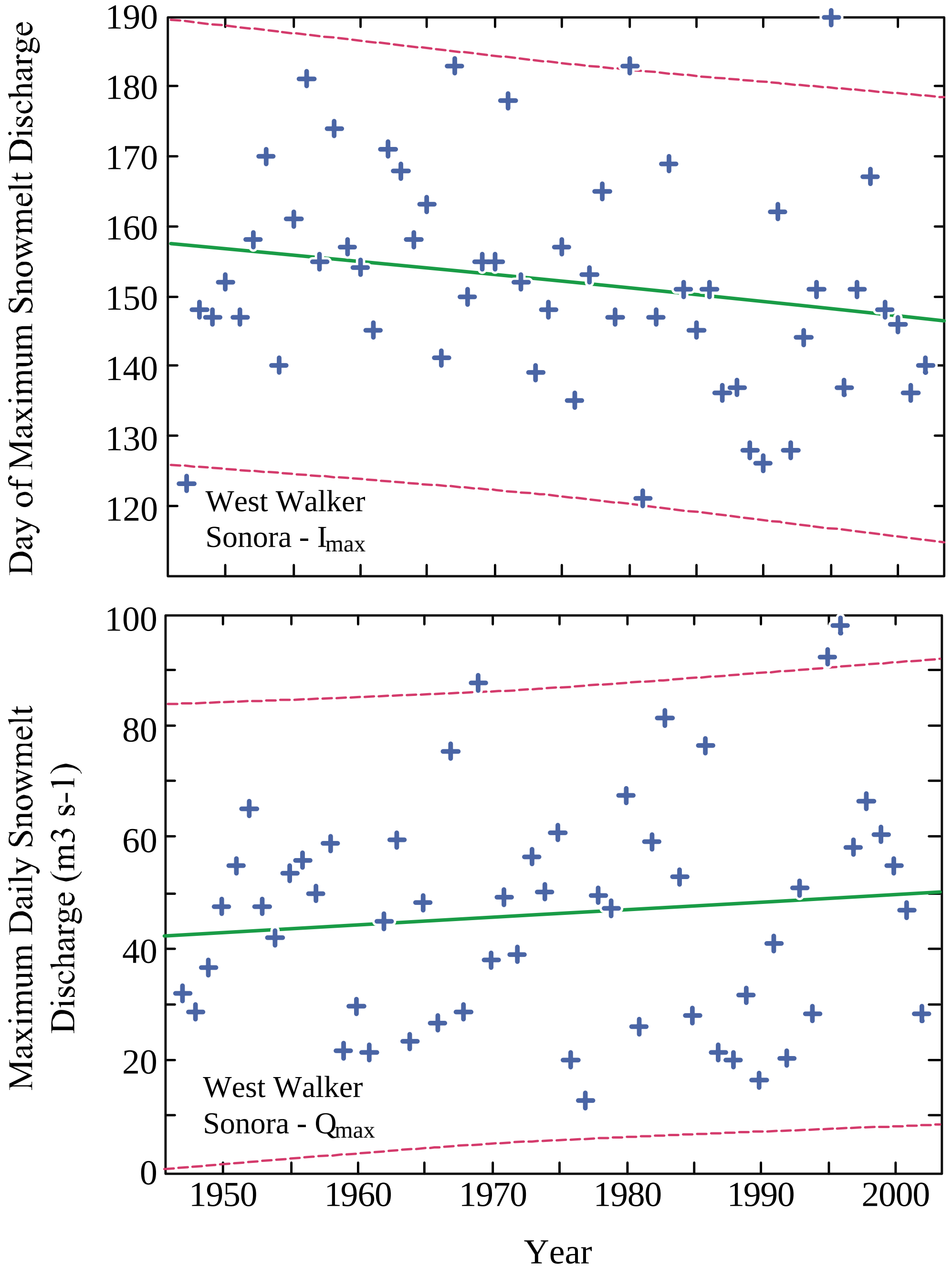

Figure 7: top) the long-term trend in earlier timing of MDSMD; bottom) the long-term trend in increasing amplitude of MDSMD over the same period, upper West Walker River, 1947-2002.

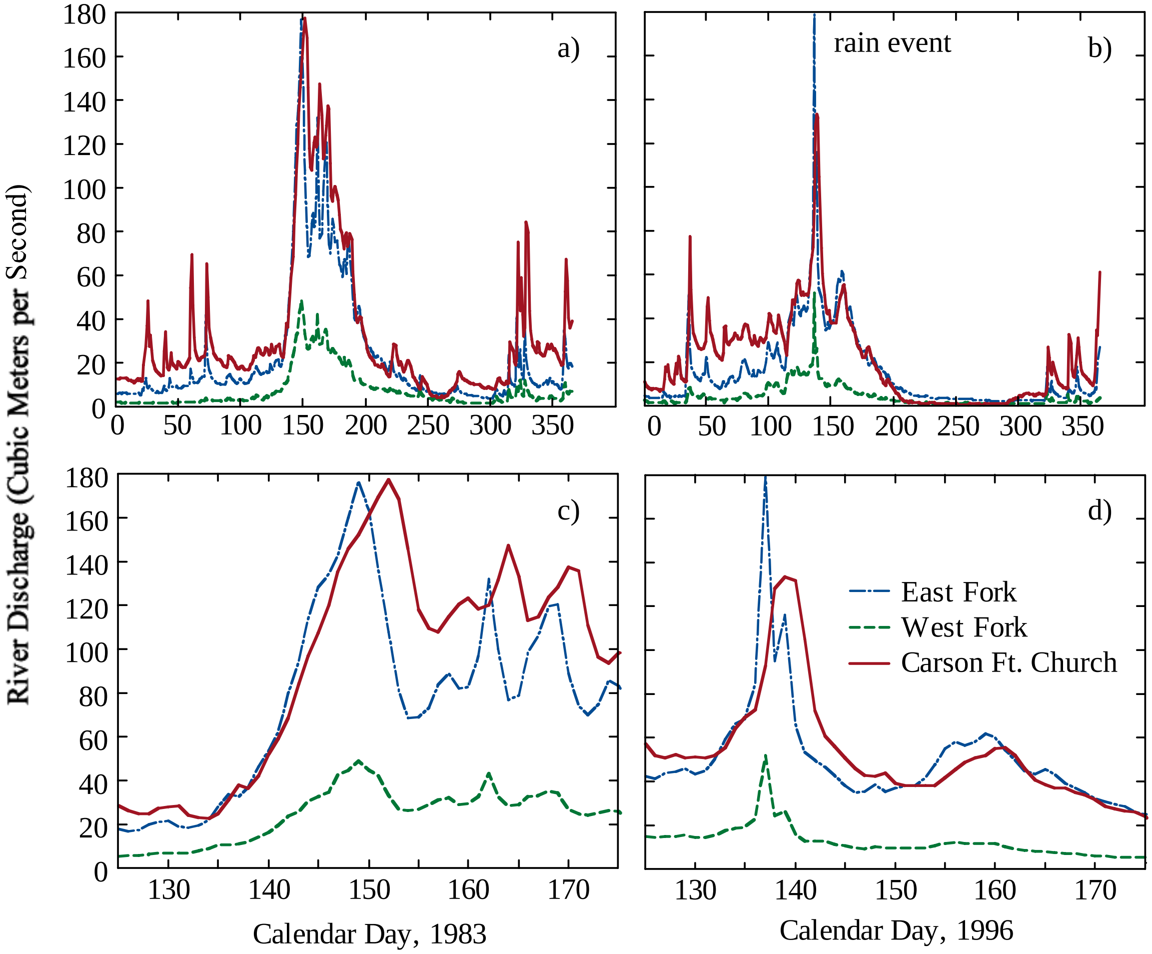

Figure 8: a) the upper (Blue), a tributary (Green), and lower (Red), daily discharge, Carson River, 1983; b) same as (a) but including a large rain event in 1996, c) same as in (a) but with the MDSMD image enlarged (note the similarity in upper (Blue) and lower (Red) magnitude (with a downstream lag)), d) the 1996 rain event is not observed downstream.

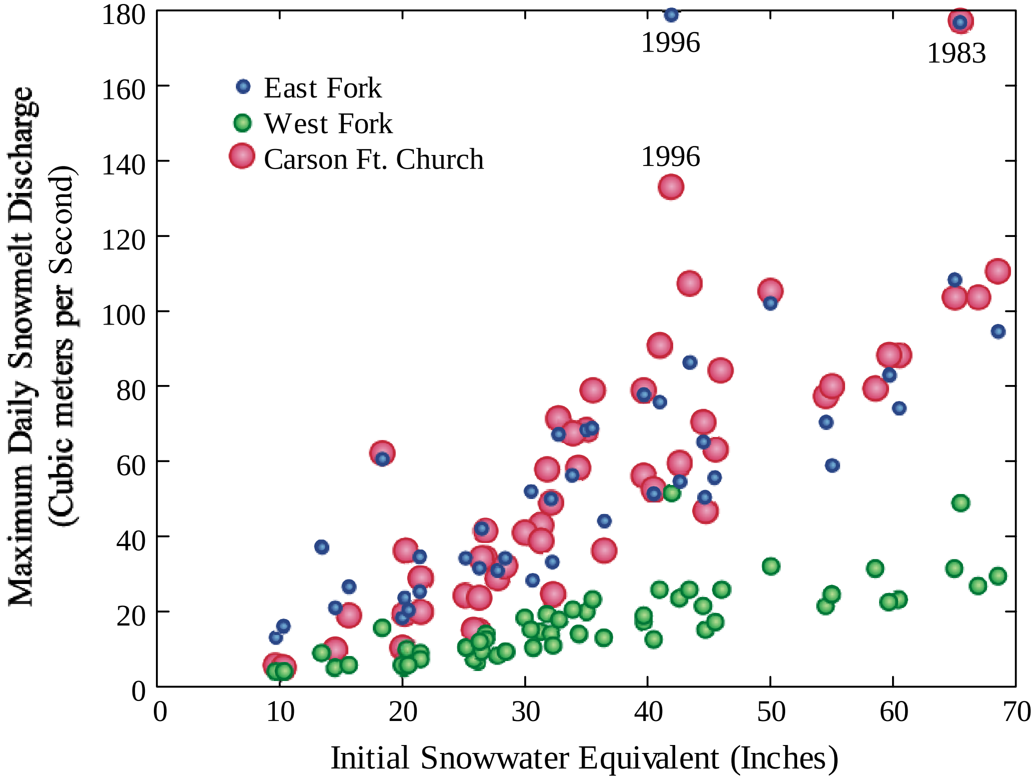

Figure 9: Maximum daily snowmelt discharge for the Carson River, upper (Blue), tributary (Green), and lower (Red), as a function of initial snow water equivalent. Note that the downstream difference was large for the rain event and small for maximum daily snowmelt discharge.

DISCUSSION AND FUTURE WORK

The difference in strength of MDSMD magnitude and timing is, in part, because a high initial swe is necessary for high amplitude in MDSMD. The factors that influence timing, however, are not well defined. MDSMD timing is measured during a period when air temperatures are relatively high, snow pack is diminishing, and SMD continues whether or not air temperatures are low-high or high-high in late spring or early summer (but continues at different rates). MDSMD amplitude also correlates strongly with swe because SMD peaks before air temperature peaks (i.e. the alpine watersheds are under saturated with snow). If MDSMD peaked at the same time as air temperature, the linear correlations could weaken.

Because snowmelt-driven discharge is a measured flow from much of the watershed above the stream gage, errors in MDSMD observations (the dependent variable) are small compared to the single point temporal and spatial sampling errors for swe (in the standard statistical regression method used, the error free independent variable). A recursive least squares regression method could improve interpretation of results compared to the linear least squares method because the errors in both variables are considered. Forecasts are expected to improve by reducing spatial sampling error, such as in using both a lower and higher elevation swe input for predicting MDSMD, and by reducing temporal sampling error, with an adjustment for time variations in initial swe.

Other topics for research are the effects of elevation, geomorphology (such as slope aspect), trends in climate variables and the associated responses in MDSMD. MDSMD time series are noisy, and therefore not a good choice in studying the effects of trends in the climate driving variables, but the motivation to do so is that MDSMD is an important property of SMD. Knowledge of MDSMD is important to reservoir managers and MDSMD marks the transition from rising to declining SMD which is of scientific interest. Finally, if the river discharge gage was discontinued, as in several watersheds in this study, obviously the quality of the results of the forecast cannot be directly accessed but could be estimated by correlation with the other watersheds.

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