Streamflow Predictability in the Upper Versus Lower Colorado River Sub-Basins

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ABSTRACT

Streamflow in the Upper Colorado River in the Western United States is always snowmelt dominated, while the Lower River's perennial streamflows are snowmelt dominated only 50% of the time. The magnitude and timing of peak flows is important for water resources management. In the Upper Basin the annual maximum daily discharge usually occurs in May or June, while in the Lower Basin this peak is observed to occur in any month except May or June. The timing of one-half of the runoff volume is used as a second measure of the variability in timing and magnitude of streamflows. For the Upper Basin, nine watersheds are used to illustrate streamflow trends, with the Yampa River used as a sample sub-basin. For the Lower Basin, five watersheds are used, of which the Salt and Little Colorado Rivers are used as sample sub-basins. The differences in monthly flow variation over 20-year time periods (1920–1939, 1940–1959, 1960–1979, and 1980–1999) are substantial for the Salt and Little Colorado Rivers but not for the Yampa River. There is a good correlation between snow water equivalent (SWE) and winter runoff volumes for the three sub-basins. A weaker relationship exists between SWE and non-winter flows for the two sample Lower Basin watersheds.

Keywords: peak flow, runoff volume, Colorado River, NRCS snowcourses

INTRODUCTION

Water is a crucial resource in the western United States (US); it has multiple, often conflicting uses, including urban, agricultural, industrial, and environmental. In the mid-1980s, annual water consumption averaged 44% of renewable supplies [*el-Ashry and Gibbons*, 1988]. Population increases and changes in water use practices [*Pulwarty*, 1995] may start to constrain availability. The potential for prolonged drought is possible [*Colorado Water Resources Research Institute*, 2002], and could result in water demands not being met [*el-Ashry and Gibbons*, 1988].

The snowpack is the major source of water throughout much of the western United States. From the Natural Resources Conservation Services (NRCS) snow telemetry (SNOTEL) data, *Serreze et al.* [1999] showed that on average snow accounted for 39 to 67% of the annual precipitation for different regions of the western United States. For the Colorado River, the percentage is 63% in the upper basin and 39% in the lower basin [*Serreze et al.*, 1999]. Most of this basin is a semi-arid region where the snowpack delivers a majority of the streamflow [*Doesken and Judson*, 1996], that subsequently supplies users living downstream of the snowpack. There are substantial seasonal and annual differences in snow water equivalent (SWE) estimated from SNOTEL data [*Fassnacht et al.*, 2003].

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This paper examines the variability in streamflow of the Upper and Lower Colorado River sub-basins. The objectives are as follows: i) to examine whether the differences in the magnitude and timing of the annual maximum daily peak flows and annual runoff volumes are indicative of the differences in the average daily streamflow for various sub-basins, and ii) to examine whether the aforementioned differences are a function of the observed SWE for the Yampa River in the Upper Basin and the Salt and Little Colorado Rivers in the Lower Basin. The results presented herein are preliminary, and are meant to illustrate trends and patterns.

STUDY AREA AND METHODS

The study area was the Colorado River Basin in the southwestern United States. A majority of the snow is located in the Upper Colorado (drainage area 277,000 km^2), which has an elevation range of 975–4260 m with an average elevation of 2150 m. The Lower Colorado (drainage area 346,000 km^2) has an elevation range of 24–3851 m and an average elevation of 1310 m. Almost 60% of the upper basin, but only 16% of the lower basin, is above 2000 m. The snow in the Lower Colorado River Basin is located along the Mogollan Rim in east central Arizona, up through the Colorado Plateau approaching the Grand Canyon, and western New Mexico.

Throughout the Colorado River Basin, 14 rivers have long-term stream-flow gauging sites that can be considered to have limited regulation (Figure 1). These sub-basins vary in size from 264 to 20,442 km^2 and have at least 57 years of record (Table 1). Only four of the nine Upper Basin gauges (Uncompahgre, Green, Yampa, and Animas), but four of the five Lower Basin gauges (Little Colorado, Gila, Salt, and Verde) are considered suitable for the USGS Hydro-Climatic Data Network (HCDN). An upstream station on the Dolores River has been included in the HCDN, while downstream stations have been included in the HCDN for the Colorado, Gunnison, San Juan, and San Francisco Rivers. The HCDN does not include a station for the San Juan River. The stations included in the HCDN either had a shorter period of record and/or were located downstream of "larger" control structure. Further comparison of watershed characteristics should be made to the HCDN.

Table 1. Minimally or unregulated perennial streamflow gauging stations in the Colorado River Basin with a continuous streamflow record for more than 50 years that were used in this study. The dashed line denotes the division between the Upper and Lower Basins.

gauge name	USGS gauge number	basin area (km^2)	length of record (years)	annual daily maximum streamflow (m^3/s)			annual runoff volume (mm)		
				max	min	mean	max	min	mean
Colorado R above Grand Lake	09011000	264	66	20.1	0.300	2.56	617	79.5	306
Gunnison R at Gunnison	09114500	2620	75	105	4.61	21.4	436	87.4	258
Uncompahgre R at Colona	09147500	1160	89	41.4	1.398	7.54	440	72.5	205
Dolores R at Dolores	09166500	1305	90	84.7	1.031	12.2	541	59.5	296
San Miguel R at Placerville	09172500	803	65.5	34.1	1.362	6.75	460	98.9	265
Green R at Warren Bridge	09188500	1212	70	81.1	2.34	14.2	566	206	369
Yampa R near Maybell	09251000	8828	85.4	282	3.32	44.0	307	48.2	157
San Juan R at Pagosa Springs	09342500	771	66	68.7	0.893	10.5	845	68.3	429
Animas R at Durango	09361500	1792	89.4	137	4.46	23.0	682	119	406
Little Colorado R at St. Johns	09384000	1823	62	10.3	0.020	0.622	35.1	1.44	10.8
San Francisco R near Glenwood Springs	09444000	4279	75	66.3	0.346	2.51	73.2	2.91	18.5
Gila R near Solomon	09448500	20442	79.4	279	1.35	13.0	97.4	4.41	20.1
Salt R at Roosevelt	09498500	11148	89	489	3.69	25.2	261	15.3	71.4
Verde R above Horseshoe Reservoir	09508500	14223	57.1	458	2.60	16.0	140	11.1	35.6

In the Lower Basin, the Gila, Salt, and Verde Rivers flow through the city of Phoenix, Arizona, which is the largest urban area in the entire Upper and Lower Basin. These three rivers are the major natural sources of surface water for the city; the Central Arizona Project brings water from the Colorado via canal. The Salt and Verde Rivers flow into the Gila River on the west side of the city of Phoenix, and the Gila River is the only significant into the Colorado River, when its flows that far downstream. There is often little to no streamflow in the Gila River downstream of the city of Phoenix, due to infiltration, evaporation, and water usage. The San Francisco River flows into the Gila River upstream of the confluence of the Gila and the Salt-Verde.

To examine differences in streamflow characteristics, the Yampa River will be the focus for the Upper Basin, and the Salt and Little Colorado River for the Lower Basins. The drainage area of the Yampa and Salt Rivers is comparable and they seem to be representative of the other watersheds in their respective basin. All other gauges in the Upper Basins are less than 30% the size of the Yampa, while the drainage areas of the Lower Basin gauges are either much smaller or larger. The characteristics of the average daily streamflow for all gauges in the Upper Basin are similar (Figure 2). They are similar among four of the five Lower Basin gauges, with the exception of the Little Colorado River (Figure 2). Therefore, streamflow data from the Little Colorado River gauge will also be used in the investigation.

The accumulated SWE for headwater snowcourse sites (obtained from the *Natural Resources Conservation Service*, 2004a) was compared to the cumulative winter runoff volume. The length of the winter period is defined by the NRCS runoff forecasting [e.g., *Natural Resources Conservation Service*, 2004b] as April through July for the Yampa River, and January through April for the Salt and Little Colorado Rivers. Three snowcourse sites were chosen to represent the snow conditions of the Yampa River headwaters. The April 1st SWE was used in the analysis. Three other sites were chosen to represent the snow conditions of the Salt and Little Colorado River, which have a common divide centered at Mount Baldy, Arizona. Since the snow season is much shorter for the Lower Colorado Basin, the average SWE was used from February 1st , March 1st and April 1st observations. There was a stronger correlation between average winter streamflow and the 3-month average SWE than for any individual month's SWE. The snowcourses were chosen based on location and length of record with each having more than 60 years of data.

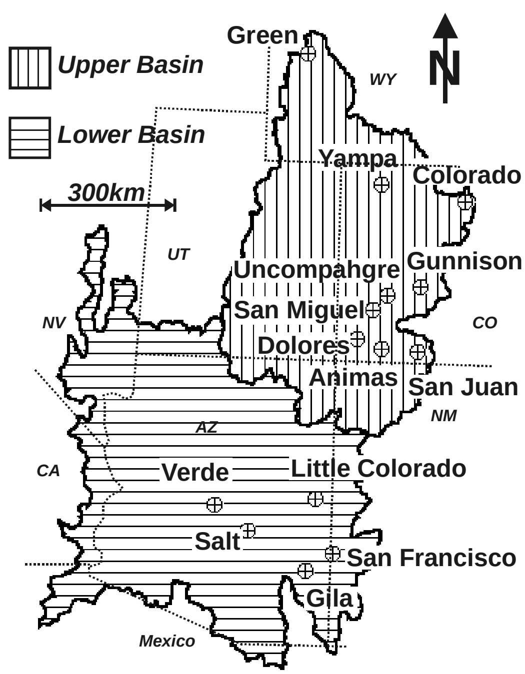

Figure 1. Locations of the streamflow gauges

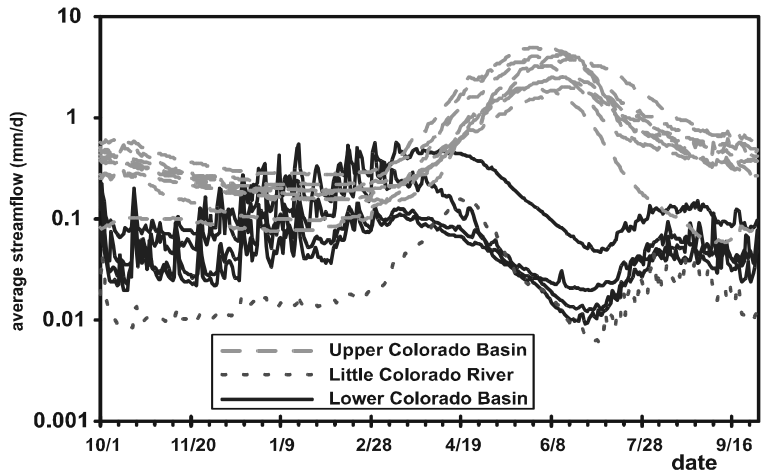

Figure 2. Average daily streamflow for minimally regulated basins with more than 50 years of record

RESULTS AND DISCUSSION

Streamflow data were obtained from the United States Geological Survey (USGS) (2004). The average annual streamflow from the three Lower Basin Watersheds (Table 1) is 9.1% of the combined streamflow of those stations and the outflow of the Upper Colorado River Basin, i.e., the Colorado River at Lees Ferry. There, the average annual streamflow is 428 m^3/s. After the filling of Glen Canyon Dam in 1965, this ratio increased to 9.8%. While these Lower Basin streamflows are less than 10% of the combined flow, understanding the magnitude and variability in their streamflow is crucial in management of the various reservoirs (e.g., Horseshoe, Roosevelt, and San Carlos Reservoirs). The combined streamflow of the nine limited regulation Upper Basin watersheds (see Table 1) is 142 m^3/s. However, these basins comprise only 18,750 km^2 of the 277,000 km^2 Upper Basin and the three Lower Basin Watersheds comprise only 45,810 km^2 of the 346,000 km^2 Lower Basin.

In the Upper Basin, the peak streamflow, as indicated by the annual maximum daily discharge, usually occurs in April, May, or June (Figure 3a), with a weak correlation between magnitude and timing of peak (r ranged from –0.064 to 0.405). The outliers in the Upper Basin may be large daily streamflows due to the North American Monsoon rather than from snowmelt. In Figure 3a, these outliers (late August through early October) are in the southern portions of the Upper Basin, specifically three years for the Animas, one for the Dolores, two for the San Juan, three for the San Miguel, and one for the Uncompahgre. Their location is closer to the North American Monsoon whose influences travel northward from the Golfo de California.

The annual maximum daily discharge for the Lower Basin occurs in all months except May and June, with limited occurring in November and December (Figure 3b). Annual peak discharges in July through September are flows induced by the North American Monsoon, January through April flows are snowmelt driven. October and November peaks are possibly significant fall rains coupled with low snow accumulation and weak North American Monsoon precipitation persistence and/or intensity. Further examination is beyond the scope of this paper.

The timing of half the annual runoff for the Upper Basin (Figure 4a) illustrates that these nine watersheds are snowmelt dominated with streamflow during the remainder of the year being significantly less, if not the daily peak (Figure 3a), than the persistence of snowmelt streamflow. There are at least seven months of flows prior and at least three months after the occurrence of one-half the annual runoff, with the exception of one year for the Animas. This matches the large late August peak in Figure 3a. The timing is a function of the start and end of the period considered, i.e., the water year. A majority of the flow in the Upper Basin is from snowmelt. In the Lower Basin, more than 50% of the streamflow is considered to originate as snowmelt 62% and 56% of the time for the Salt and Little Colorado Rivers, respectively.

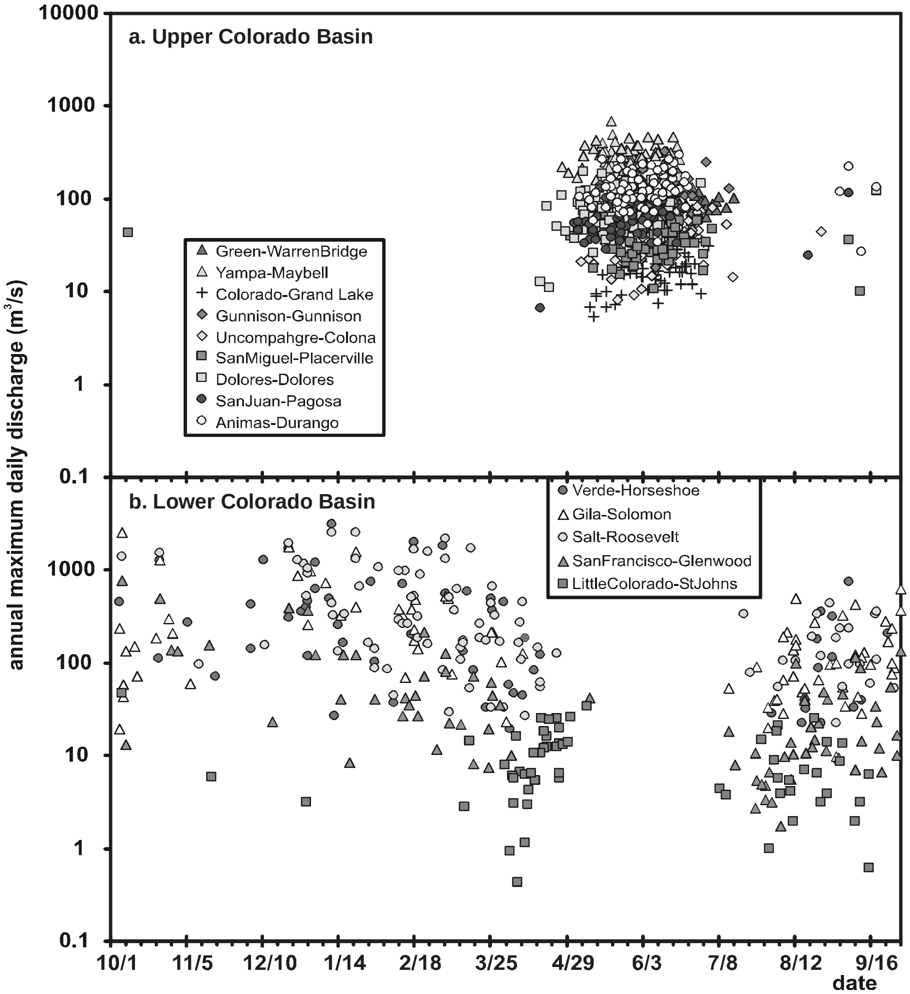

Figure 3. Magnitude versus timing of annual maximum daily discharge for gauges in the a) Upper Basin, and b) Lower Basin

For the Lower Basin, the half runoff volume timing occurs from early October through late August (Figure 4b). Figure 4b can be divided into periods that correspond in part to the annual maximum daily discharge (Figure 3b). The majority of the half runoff volume occurs during the winter months (February through May). Others occur in May through August, corresponding to North American Monsoon peaks, i.e., a majority of the annual water flowing late in the water year. Most of these were for the San Francisco, Gila, and Little Colorado Rivers. Some occur in December and January, illustrating a majority of the annual flow occurring early in the water year. Similarly, but more extreme, two occurred in early October and three in early November. This indicates large flows in early October. In 1984, the three earliest occurred: October 2nd on the San Francisco, October 4th on the Gila, and November 1st on the Little Colorado. The other two November occurrences were in 2001 (12th on the San Francisco and 15th on the Gila). Most of the timing is mid-year for the Salt and Verde Rivers, which may indicate less of an influence from the North American Monsoon and more from snowmelt; the latest for the Verde River is May 15th, 1951 with only three other occurring in the previous 33 days, i.e., after April 12th. The timing of half the annual runoff should be investigated further, as a function of snowfall and annual precipitation.

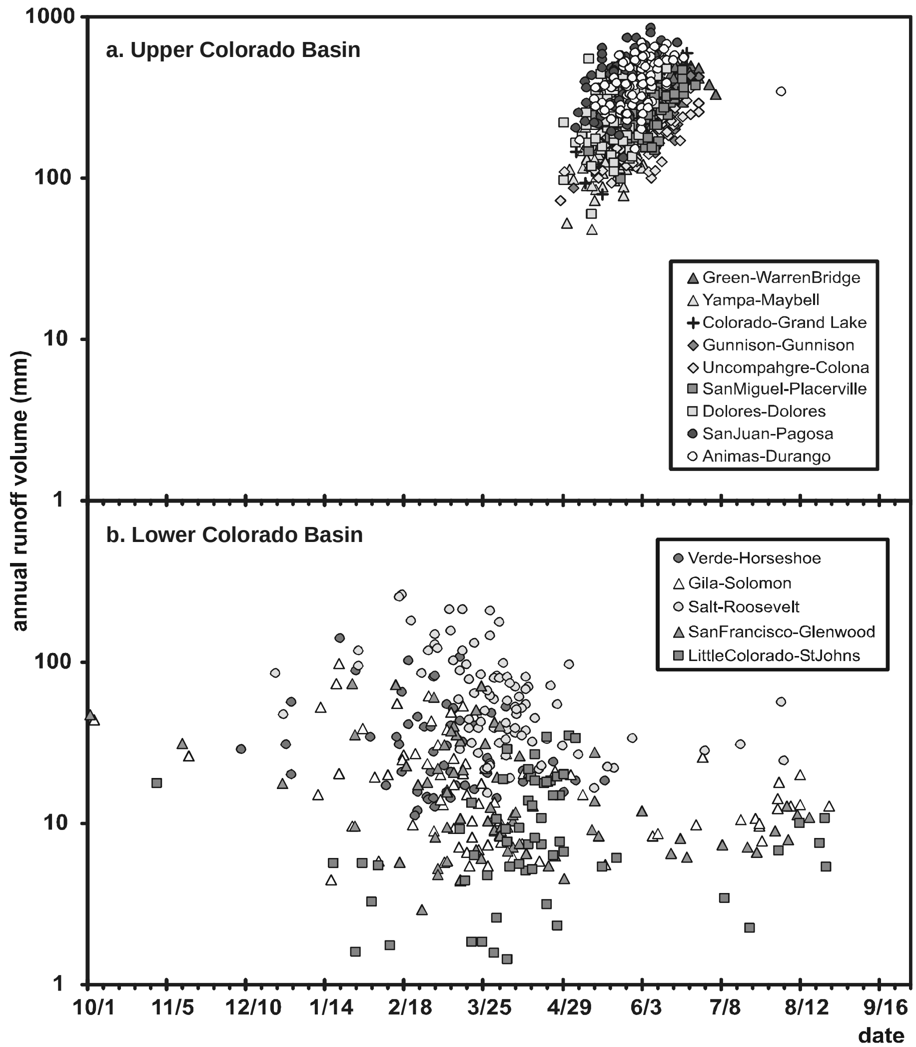

Figure 4. Magnitude of the annual runoff volume versus the timing of half the runoff volume for gauges in the a) Upper Basin, and b) Lower Basin

The average daily streamflow plots are much smoother for the Upper Basin watersheds than the Lower Basin watersheds (Figure 2). The monthly streamflow coefficients of variation (COVs) are lower for the Yampa than the Salt and Little Colorado Rivers (Figures 5a, b, and c). These plots represent 20-year periods, except 1941 to 1959 for the Little Colorado (Figure 5c). For the four time periods, there is limited difference for the Yampa River (Figure 5a), with 1980 to 1999 having the largest variation. There are similar overall average variations for the three periods from 1940 through 1999 for the Salt River. However, the period from 1920 to 1939 had approximately 15% less variation (Figure 5b). However, there are differences in the monthly coefficients of variation. There are less than 4% differences in the annual coefficient of variation between the latter three periods for the Little Colorado River (Figure 5c), yet monthly differences are larger than for the Salt.

As expected, higher coefficients of variation for the Salt and Little Colorado Rivers relative to the Yampa River correspond to more scatter in the magnitude and timing of the annual maximum daily peak flows and annual runoff volumes. The Upper Basin watersheds with tightly clustered annual maximum daily peak flows and annual runoff volumes have the lowest coefficient of variation in monthly flows. The southern Upper Basin watersheds that have outliers in Figure 4a have larger COVs than those without.

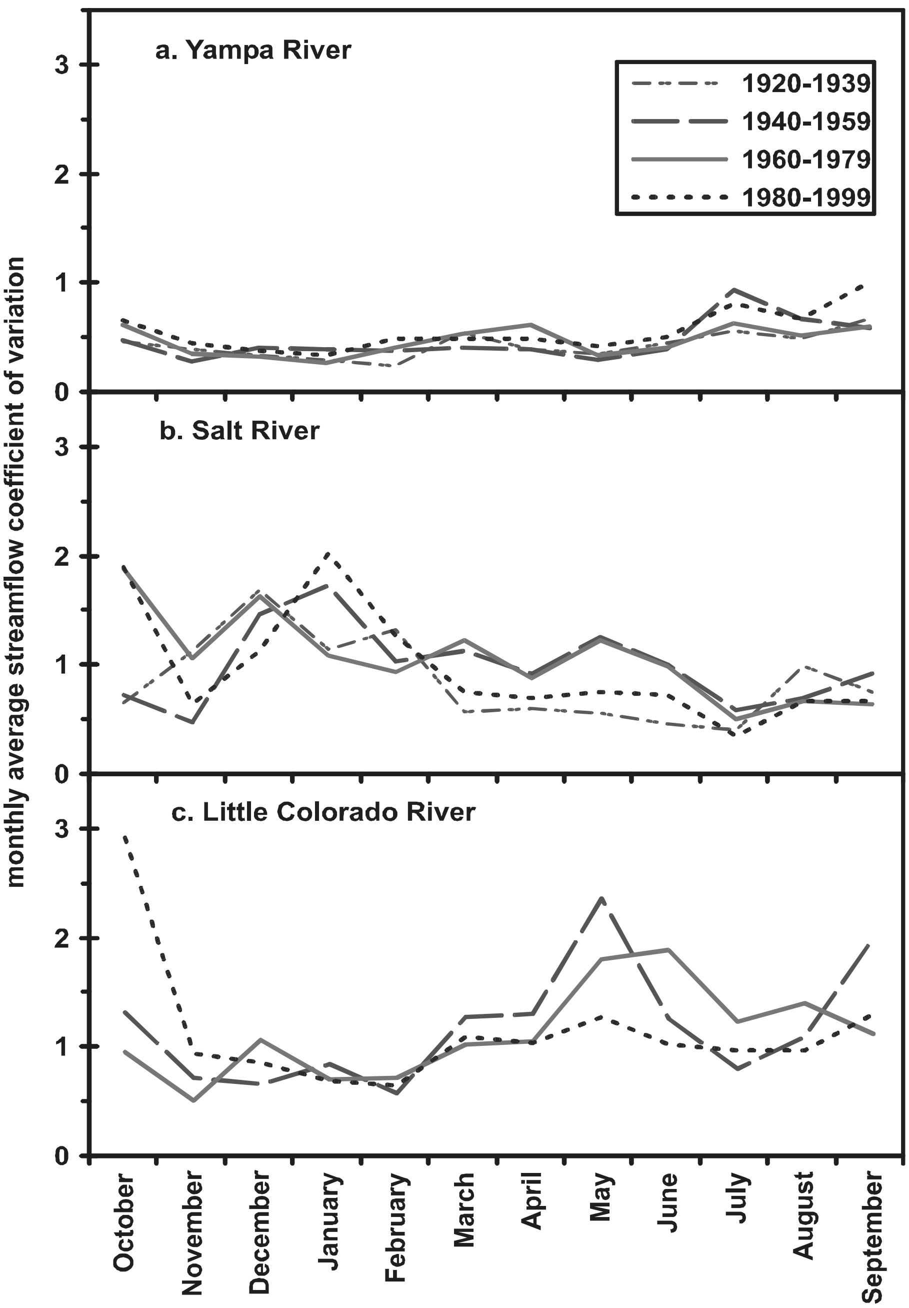

Figure 5. Monthly streamflow coefficients of variation for 20-year periods for a) the Yampa River, b) the Salt River, and c) the Little Colorado River

The correlation coefficient between SWE and winter runoff volume (Table 2a) are on average (for the three stations) the same for the Yampa and the Salt, but 15% higher for the Little Colorado. This is surprising due to the larger COV for the Little Colorado compared to the other watersheds. The Salt and Little Colorado Rivers share the same divide along the Mogollan Rim, but the snowcourse sites are within the Salt watershed. Snow accumulation in the Little Colorado watershed may be better represented by the selected snowcourse stations than for the Salt. Snow accumulation is over a much smaller area in the Little Colorado than the Salt, as seen by the average normalized runoff volume in Table 1. Accumulation may be more consistent.

There is little correlation between SWE and non-winter runoff volume for the Yampa River, but a relationship exists for the Little Colorado River and to a greater extent the Salt River (Table 2b). Some of the relationship between the El Niňo Southern Oscillation, the North American Monsoon, SWE, and streamflow have been investigated [e.g., Cayan, 1996; Clark *et al.*, 2001; Lo and Clark, 2002]. These relationships need further study, especially given the scatter illustrated by the Lower Basin (Figures 3b and 4b) as compared to Upper basin (Figures 3a and 4a). The actual length of winter flows and the representativeness of the single or three date SWE measurements should be examined in more detail.

Table 2a. Correlation coefficients for winter runoff volumes versus snowcourse SWE for the Yampa, Little Colorado, and Salt Rivers. For the Yampa River, the winter runoff volume is for April through July and the SWE is for April 1st. For the Little Colorado and Salt Rivers, the winter runoff volume is January through April and the SWE is the average of February, March and April 1st.

	snowcourse station					
gauge name	06J03	06J01	06J15	09S04	09S06	09S07
Yampa R near Maybell	0.613	0.732	0.683	—	—	—
Little Colorado R near St. Johns	—	—	—	0.785	0.811	0.724
Salt R near Roosevelt	—	—	—	0.668	0.672	0.698

Table 2b. Correlation coefficients for non-winter runoff volumes (months not included above in Table 3) versus snowcourse SWE for the Yampa, Little Colorado, and Salt Rivers

	snowcourse station					
gauge name	06J03	06J01	06J15	09S04	09S06	09S07
Yampa R near Maybell	0.111	0.186	0.167	—	—	—
Little Colorado R near St. Johns	—	—	—	0.417	0.434	0.481
Salt R near Roosevelt	—	—	—	0.531	0.580	0.539

ACKNOWLEDGEMENTS

Anne Sawyer of Colorado State University is thanked for reviewing this paper and providing very useful comments for future work.

REFERENCE

Cayan, D.R., Interannual climate variability and snowpack in the western United States, *Journal of Climate*, 9, 928–948, 1996.

Clark, M.P., M.C. Serreze, and G.J. McCabe, Historical effects of El Niňo and La Niňa events on the seasonal evolution of the montane snowpack in the Columbia and Colorado River Basins, *Water Resources Research*, 37(3), 741–757, 2001.

Colorado Water Resources Research Institute, *Colorado Drought Conference: Managing Water Supply and Demand in the Time of Drought*, Conference Proceedings, CWRRI Information Series Report No. 96, 2002.

Doesken, N.J., and A. Judson, *The Snow Booklet: A Guide to the Science, Climatology, and Measurement of Snow in the United States*, Department of Atmospheric Sciences, Colorado State University, Fort Collins CO, 1996.

el-Ashry, M., and D. Gibbons, *Water and Arid Lands of the Western United States*, 415 pp., Cambridge University Press, New York, 1988.

Fassnacht, S.R., K.A. Dressler, and R.C. Bales, Snow water equivalent interpolation for the Colorado River Basin from snow telemetry (SNOTEL) data, *Water Resources Research*, **39**(8), 1208, doi:10.1029/2002WR001512, 2003.

Lo, F., and M.P. Clark, Relationships between spring snow mass and summer precipitation in the southwestern United States Associated with the North American Monsoon System, *Journal of Climate*, 15, 1378–1385, 2002.

Natural Resources Conservation Service, *NRCS National Water and Climate Center—Snowcourse Data Network—Snow Course Data*, U.S. Department of Agriculture, URL: <*http://www.wcc.nrcs.usda.gov/snowcourse/sc-data.html*>, 2004a.

Natural Resources Conservation Service, *Colorado Basin Outlook Report April 1, 2004*, Colorado State Snow Survey, US Department of Agriculture, Lakewood CO, 2004b.

Pulwarty, R.S., Adaptive management of the Colorado River: The role of science and scientists, in *U.S. Department of Interior Glen Canyon Environmental Studies: Aquatic, Geomorphic and Climatic Information Integration Group Report*, Flagstaff, AZ (ed. T. Melis and D. Wedner), pp 36–49, U.S. Government Printing Office, Washington DC, 1995.

Serreze, M.C., M.P. Clark, R.L. Armstrong, D.A. McGuiness, and R.S. Pulwarty, Characteristics of the western United States snowpack from snowpack telemetry (SNOTEL) data, *Water Resources Research*, 35(7), 2145–2160, 1999.

Slack, J.R., and J.M. Landwehr, *Hydro-Climatic Data Network (HCDN): A U.S. Geological Survey streamflow data set for the United States for the study of climate variations, 1874–1988*, US Geological Survey Open-File Report 92-129, Reston Virginia. [Available at *http://water.usgs.gov/pubs/of/ofr92-129/content.html*]

United States Geological Survey, *Surface-Water Data for the Nation*, U.S. Department of Interior, URL: <*http://waterdata.usgs.gov/nwis/sw*>, 2004.