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Variability of low flow magnitudes in the Upper Colorado River Basin: identifying trends and relative role of large-scale climate dynamics

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Abstract

Low flow magnitude in a head water basin is important for planners because minimum available amount of water in a given time period often leads to concerns regarding serious repercussions, in both up and downstream regions. This is a common scenario in arid region like Colorado River basin located in the southwestern US. Low flow variability in Colorado River is due to complex interactions between several natural and anthropogenic factors; but we aim to identify the relative role of climate on varying low flow magnitudes at different spatial locations. The research questions we aim to answer are: *Is there a systematic variability in water availability during the driest time of a year or season? How does that vary across locations and is there a link between large-scale climate and low flow variations?* Towards that aim we select 17 stream gauge locations, which are identified as "undisturbed" meaning that these stations represent near-natural river flow regimes in the headwater region of Colorado River, which provides a useful resource for assessment of climate and hydrology associations without the confounding factor of major direct (e.g. water abstraction) or indirect (e.g. land-use change) human modification of flows. A detailed diagnostic analysis gives us fair understanding on the variability of low flow magnitude that is explained by climate. We also present spatial heterogeneity of hydro-climatological linkages that is important for suitable adaptive management measures.

1 Introduction

Variability and change in stream flow can directly influence water supply (both quantity and quality) for domestic, agricultural, industrial, ecological, and other needs. Every populated river basin in the world will experience changes in river discharge; some are expected to have large increases while other river basins will likely experience the water scarcity (Palmer et al., 2008). Understanding variability of the volume of stream flow is important because very high flows can cause damaging floods and erosion, while very low flows can fail to provide adequate water supply, diminish water quality, and affect important ecological services (Heicher, 1993; Smakhtin, 2001; Curran et al., 2012). Anticipating what the seasonal and annual minimum flow might be in the headwater locations of a river is important for up and downstream water management purposes because existing evidences suggest that water scarcity due to low river flow could also be one of the main drivers of societal and cross-boundary conflicts (Gleick and Palaniappan, 2010; Gleick, 2010, 2014). Complex interactions among anthropogenic factors, ecosystem processes, and climate, influence the long-term water supply from the headwater basins and as such minimum river flow is a result of complex interactions between human and biophysical features, which also differs from one region to another (Jones et al., 2012). Hence, characterizing lower tail of river flow distribution demands more attention than it has received so far due to integral impacts of persistent low flow conditions in a river costing more than ever thought in history.

Water resources in the southwestern United States, are especially scarce and climatic changes may cause significant alterations in water availability, quality, and demand. The hydrology of the southwestern United States is already characterized by strong variability on seasonal to multiannual time scales, reflecting its sensitivity to fluctuations in large-scale atmospheric circulation patterns from the Pacific Ocean, the Gulf of California, and the Gulf of Mexico (Seagar et al., 2007). Amongst major river basins, Colorado River is the critical source of water for 7 states in the arid southwestern United States (especially for high municipal and industrial demands), and that, this river has a history of going under low flow conditions (i.e. flow going under a minimum threshold condition) in the past (USGS, 2004; Meko et al., 2007; Ellis et al., 2010; Gleick, 2010). In addition, population growth, urban and industrial expansions within the past decades enhanced this effect. It has been reported in the scientific literature that the Colorado River flow is expected to reduce under future warming scenarios due to a combination of strong temperature-induced runoff curtailment, reduced annual precipitation, and increased evapo-transpiration. Another risk to Colorado River stream flow is multi-decadal droughts, which is also expected to change under climate change

(IPCC AR4; IPCC AR5). Therefore, impacts of drought conditions on the river flows, especially in the driest time of any given season is also expected to change (Meko et al., 2007; McCabe et al., 2007; Ellis et al., 2010; Gleick, 2010; Cook et al., 2010; Gao et al., 2011; Miller and Piechota, 2011; Seager et al., 2013), but little is known regarding how the low flow characteristics changed over time in response to change in climate and its effects on local hydrology.

There is complexity and heterogeneity of low flow dynamics in a river basin. Therefore, it is difficult to generalize characterization of low flow. Low flow, defined in many different ways (Sect. SII in the Supplement), could be a sole or combination of multiple factors in different seasons. Such factors may include slowly flowing ground water discharge, surface discharge from lakes, marshes, or melting glaciers, basin precipitation, basin temperature and evaporation rates, basin soil, topography, geology and vegetation, river channel characteristics, and various man-induced effects (Smakhtin, 2001). For instance, in summer time (July through October), low flows of most part of the United States, are usually derived by base flow (Reilly and Kroll, 2003; Flynn, 2003). On the other hand, in cold or mountainous regions, low flows are subject to the spacial influences of ice, snow or glacier melting in addition to the usual basin parameters (Smakhtin, 2001; Reilly and Kroll, 2003; Miller and Piechota, 2011; Curran et al., 2012; EPA, 2012). Therefore, we conjecture that climate is linked with low flow characteristics and those links vary for different locations because of variable physiographic parameters.

This leads to the science questions: *How heterogeneous are the variability of low flow conditions in the headwater basin of Colorado River? How are season specific low flows linked with synoptic ocean–atmospheric conditions? Where is that signal evidently strong and where is it weak? How different those linkages are for diverse locations in the headwater basin?*

Through the Colorado River Compact, the Upper Colorado River Basin (UCRB) supplies water and hydropower for much of the southwestern United States and hence low flow dynamics of UCRB has large influence on both the up and the downstream water supply. These scientific questions will enable us to understand the statistical characteristics of regional low flow variability in this important river basin as well as capture their physical connections to large-scale ocean–atmospheric systems. Our research findings will support scientists and engineers to develop prediction tools that assist in climate informed and timely water management decisions during potential crises, as well as maintaining the minimum flow conditions in the river to sustain ecosystem services.

The paper proceeds as follows. Section 2 describes the datasets used, Sect. 3 summarizes calculation of low flow statistics, Sect. 3 explains results and related discussions, and Sect. 4 summarizes the findings.

2 Data

We selected 17 “undisturbed” stream gauges in UCRB, which primarily contribute to the largest amount of total Colorado River Basin stream flow (McCabe et al., 2007; Gao et al., 2011). Consideration of the undisturbed stations minimizes the human induced effects on the natural flow and captures natural variability and changes. We downloaded the daily river flow data from USGS Hydro-Climatic Data Network 2009 (Lins, 2012). The description of the data is found in the Supplement (Sect. SI). Table 1 in the Supplement lists the stations information and Fig. 1 shows the geographic locations of those stations as well as length of the data ranging from 25 to 61 years.

To study large-scale climatological patterns, we used global Surface Temperature (ST) and Mean Sea Level Pressure (MSLP) data from 1949–2011 from NCEP/NCAR reanalysis V1.0 monthly diagnostic products (Kalnay et al., 1996), and daily gridded (0.25 × 0.25) precipitation data (Ptotal) from 1949–2011 from Climate Prediction Center (CPC) for the entire continental US (http://www.esrl.noaa.gov/psd/data/gridded/data.unified.html). We downloaded the climate datasets in ready to analyze forms from the International Research Institute for Climate and Society Data Library (http://iridl.ldeo.columbia.edu).

3 Calculation of low flow statistics

To calculate low flow statistics, we considered climate years that extends from 1 April–31 March. This ensures the continuity of the data during typical low-flow periods, as suggested by previous research (Ries and Friesz, 2000; Flynn, 2003; Reilly and Kroll, 2003; Pyrce, 2004; Risley et al., 2008; Martin and Arihood, 2010; Curran et al., 2012; EPA, 2012). Daily mean flows for all complete climatic years of record are used to determine low-flow statistics for all the 17 stream-gaging stations. Low-flows in streams can be characterized in many ways but in the United States, the 7 day low flow – annual series of the smallest values of mean discharge over any 7 consecutive days (q7) – is a common method for determining the low flow magnitude (Ries and Friesz, 2000; Smakhtin, 2001; Flynn, 2003; Pyrce, 2004; Reilly and Kroll, 2003; Risley et al., 2008; Martin and Arihood, 2010; Curran et al., 2012; EPA, 2012). We follow this approach in this research. Annual q7 occurrence is generally expected to happen in the driest season, which is consistent with our finding – we note that q7 occurs in the beginning of spring and/or summer for UCRB, but, different stream gauges experience q7 in the different months (Table S2 in the Supplement). As mentioned before, in the summer time, low flow conditions in most part of the United States is generally driven by the base flow (Reilly and Kroll, 2003; Flynn, 2003), and in winter, that subject to the influences of ice, snow or glacier melting. Thus, in addition to annual low flows, it is also crucial to study variations of low flows in different seasons (Khaliq et al., 2008). Hence, in addition to annual q7, we also considered studying q7 in different traditional seasons, namely December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), and September-October-November (SON), which is largely non-existent in the literature.

4 Results and discussions

This section presents an in depth descriptive analysis of low flow statistics at UCRB locations. That helps to detect the seasonal and annual variability patterns of q7. Following that we report outcomes of a detailed correlational investigation that identify relationships between seasonal low flow statistics and concurrent large-scale seasonal climatic patterns.

4.1 Low flow variability and trends

Summary statistics. Figure 2 shows year-to-year variation of annual q7 magnitude – annual smallest values of mean discharge over any 7-consecutive days, and those for the traditional seasons are shown in Fig. S1 in the Supplement. Figure 2 (and Fig. S1 in the Supplement) indicates that annual (and seasonal) low flow magnitude has high spatio-temporal variability. This is expected because river basin characteristics play a major role for q7 variation. Spatial variability magnitudes of q7 are also found in the summary statistics Table 1 for annual and Tables S3–S6 in the Supplement for the traditional seasons.

Of the major assumptions in a correlational study is normal distribution idea. Since q7 falls at an extreme tail of the daily mean flow distribution, non-normal behavior can be expected. Therefore, to detect the non-normal behavior in q7 time series for different stream gauge locations, we estimated skewness and kurtosis values and reported them in the summary statistics tables. As those values indicate, annual and seasonal q7 distributions are normal in general, because, as a rule of thumb, they have an absolute skewness value less than 3 and an absolute kurtosis value less than 10.

Cross-correlation analysis. To determine co-variability, we conducted a cross correlation analysis between q7 time series for different stream gauge stations. Main Tables 2 and 3 lists the annual and JJA cross-correlation analysis results and Tables S7–S9 in the Supplement list the other traditional season results. These tables indicate that q7 magnitudes in most stations are positively correlated with each other; which is most

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prominent and statistically significant for the cases in the summer (JJA), as in Table 3 and followed by SON (Table S9 in the Supplement). This finding indicates that variability of low flow at multiple locations might be linked with common external factors, for JJA in particular. Generally, stations close to each other have highest positive significant correlations.

Monotonic and periodic trends assessment. Impacts of global climate change as well as large scale natural variability is felt locally. Therefore, it is imperative to look at whether there have been any significant trends (monotonic as well as periodic) in seasonal and annual low flow statistics and how they compare amongst locations. Periodic trends are also indicator for small-scale hydrological system response to large-scale circulation patterns, such as El-Nino Southern Oscillation (ENSO). We considered non-parametric Mann–Kendall trend tests to detect monotonic trends and wavelet power spectrum analysis to identify periodic trends or multi-decadal patterns. Selection of Mann–Kendall test is to allow ignoring high-frequency (i.e. multiple change point) variations.

Main Fig. 3 depicts the monotonic trend results, which reveal that trends in low-flow magnitudes exhibit fluctuating behavior in different seasons and annually. Stations, which are located close to each other, are generally showing homogeneity in significant trends. More specifically, we notice a clear division in monotonic trends in the eastern and western sides of −107.5° longitude. Annual, DJF, MAM, and SON q7 trends are negative on the west side and positive on the east side. JJA q7 trends are usually negative everywhere, except some non-significant positive trends. Negative trending patterns in the western part of UCRB, are consistent with some of the previous studies, which indicated a general trend of low flow states toward permanently drier conditions in the southwestern US due to a projected decrease in Colorado headwaters runoff and soil moisture arising from a projected increase in evaporation (USGS, 2004; McCabe et al., 2007; Gleick, 2010; Seager et al., 2007, 2013). However, positive trend patterns on the eastern part of UCRB does not follow the notion that dry will get drier and wet will get wetter, which is clearly not applicable for low flows. This monotonic trend study again indicates the importance of locally based studies and needs further investigations to look into the causes for the differences in trends.

Hydro-climatic analysis have also indicated that there is considerable non-stationarity in measured and reconstructed precipitation series as well as stream flow estimates for the Colorado River basin, which may be linked with inter-decadal, decadal, multi-decadal and even secular variations in ocean temperatures (Cook et al., 2004; Gray et al., 2004; Hidalgo, 2004; McCabe et al., 2004). To detect periodic trends in low flow magnitude, wavelet power spectrum analysis could be used. The decomposition of time series into time-frequency space permits the identification of the dominant modes of variability and determining how these modes vary in time. A few examples of periodicity of q7 magnitudes are shown in Fig. 4, all of which indicate close to 10–16 years periodicity. Rest of the test results for other stations is presented in the Tables S10 and S11 in the Supplement, which also confirms recurrent 10–16 years periodicity of q7 data. Though the exact cause of these multi-decadal variations is not fully understood yet, this dominant 10–16 years periodicity might be related to Interdecadal Pacific Oscillation (IPO), which is considered as inter-decadal ENSO-like SST (sea surface temperature) variability reported by Zhang et al. (1997) and Folland et al. (2002) that has far wider hemispheric climatic impacts (Folland et al., 2002; Dai, 2013). However, this needs further investigation to confirm the causal linkage.

4.2 Linkage with large-scale climate patterns

This section summarizes Pearson correlation patterns between low flow magnitudes (q7) and large-scale climate variables. We've considered total precipitation estimates (Ptotal), global surface temperature (ST) anomalies, and mean sea level pressure (MSLP) anomalies to determine variability of q7 dictated by climate. To do that, first, we conducted an analysis to determine the monthly combinations around q7 occurrence month (refer to Table S2 in the Supplement) when average climate conditions best explain the variance of annual q7. For example, referring to Table S2 in the Supplement, historically, annual low flow magnitudes (q7) in the Black station occurred between October and March. Therefore, to determine the best monthly combinations for average climate conditions, we considered 3 combinations of months: ONDJFM, OND, and JFM; and then carried out separate correlation analyses with annual q7. By studying the correlation pattern maps, we picked the best monthly combinations for climate conditions, as indicated in Fig. 5.

Figure 5 shows that the climate conditions over winter and spring best explain the annual q7 variability over UCRB. There are clear variations in the spatial correlation maps, which is difficult to generalize for the entire basin, but largely it is the total precipitation over the western US that is important for stations located in the west in particular. For the traditional seasons, q7 in JJA and SON indicated strong correlation patterns with concurrent climate variables, as shown in Fig. S2 in the Supplement. In general Ptotal correlation maps in Fig. S2 in the Supplement are consistent with Fig. 5 in that precipitation over the western US correlate positively with q7 magnitudes. Some previous studies indicated that during the recent 30 year, when warming of UCRB exceeded the century long rate, precipitation played a greater role in the drought increase (Gutzler et al., 2002; Hidalgo and Dracup, 2003; Balling and Goodrich, 2007; Dai, 2013). It is also found that regional sensitivity of stream flow to changes in precipitation is highest in the Midwestern regions of the US (Douglas et al., 2000; Sankarasubramanian et al., 2001), which also resonates in our finding. Some studies (e.g., Dai, 2013) detected that IPO phase changes are likely to have played a significant role for the recent trends in the precipitation and droughts. Decadal precipitation variations over the southwest, closely follow the evolution of the IPO, and the dry and wet periods are associated, respectively, with the cold and warm phases of the IPO.

Figure 5 also shows ST patterns. There is heterogeneity in response patterns but stations mainly show ENSO and IPO type signatures, for example, Mill and South Creek, both located on the south and western side of the basin and closely located to each other. MSLP patterns for these stations also indicate high correlation patterns over the western Pacific, which confirms ENSO and IPO patterns once again. Many studies indicated persistent La Nina-like cold SST anomalies in the tropical central and eastern Pacific Ocean leading to below-normal precipitation and often droughts over Southwestern North America (e.g., Seager et al., 2005; Mo et al., 2009; Wang et al., 2010); whereas warm Atlantic SSTs reduce summer precipitation over the West and central US (Kushnir et al., 2010; Feng et al., 2011). On the contrary, some studies (e.g., Mo et al., 2009) also suggested that the Atlantic influence is comparatively weak and is mainly through its modulation of the impact of ENSO-like SST forcing from the Pacific. Therefore, our studies indicate that the "direct" influence of ocean–atmospheric features is difficult to generalize for all the stations in a given river basin depicting some non-linear behavior between connections of q7 and large-scale climate moderated by other factors.

5 Summary

Low-flow statistics for the streams is important for water supply planning and design, waste-load allocation, reservoir storage design, and maintenance of quantity and quality of water for irrigation, recreation, and wildlife conservation. Colorado River is the lifeline for many states in the arid southwestern US. Water availability in the headwater basin matters a great deal for these states. In this study we aim to understand the variability of low flow conditions during different seasons as well as years. The goal was to detect how heterogeneous the variability and trends of low flow magnitudes are in a given river basin as well as to detect what role large-scale climate features play to modulate them. Since low flow is due to a complex mixture of many local physiographic factors and climatic mechanisms, it has been hard historically to generalize the low flow characterization for the entire basin. However, this study indicates that significant monotonic and periodic trends are existent for annual and seasonal low flow magnitudes, which differ in the east and western parts of the basin separated by 107.5° longitude. Furthermore, winter and spring seasonal total precipitations over the western US correlate well with q7, which could play an important role to predict the same. We anticipate that this with the basin characteristics, and ENSO and IPO conditions, are able to enhance statistical predictions of the low flow, which forms our next step of research. A skillful and timely prediction of location specific low flow statistics is important and necessary for environmental, industrial and agricultural sectors, which has an aim to keep up with the water demand for human and ecological systems during the time of water scarcity. This scientific research takes a step forward to contribute to that reason.

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Author contribution.

I. P. designed the experiments and M.P.P. carried out the analysis. I. P. and M. P. P. prepared the manuscript.

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Table 1. Summary statistics table for annual q7 time series for each stream gauge station in UCRB.

Station ID	Station Name	Mean (cfs)	Median (cfs)	Standard deviation (cfs)	Skewness	Kurtosis
9 066 000	Black Gore Creek Near Minturn, CO. (east)	1.97	1.89	0.62	0.73	1.29
9 034 900	Bobtail Creek Near Jones Pass, CO. (east)	0.69	0.66	0.13	0.49	0.49
9 066 200	Booth Creek Near Minturn, CO. (east)	0.72	0.73	0.28	1.69	6.44
9 306 242	Corral Gulch Near Rangely, CO. (west)	0.37	0.30	0.26	0.79	−0.10
9 081 600	Crystal River Ab Avalanche C, Near Redstone, CO. (east)	41.46	39.86	8.30	0.88	1.23
9 035 800	Darling Creek Near Leal, CO. (east)	1.76	1.79	0.33	0.25	0.09
9 065 500	Gore Creek At Upper Station, Near Minturn, CO. (east)	2.48	2.34	0.84	2.21	7.85
9 047 700	Keystone Gulch Near Dillon, CO. (east)	1.79	1.80	0.36	0.34	0.23
9 066 300	Middle Creek Near Minturn, CO. (east)	0.22	0.20	0.15	1.21	3.00
9 035 900	South Fork Of Williams Fork Near Leal, CO. (east)	6.77	6.73	1.63	−0.08	0.59
9 107 000	Taylor River At Taylor Park, CO. (east)	28.67	28.43	3.80	−0.30	0.18
9 352 900	Vallecito Creek Near Bayfield, CO. (west)	15.82	15.79	4.54	0.40	0.21
9 183 500	Mill Creek at Sheley Tunnel, Near Moab, UT. (west)	4.54	4.46	0.87	−0.27	1.39
9 210 500	Fontenelle C Nr Herschler Ranch, Nr Fontenelle, WY. (west)	16.73	15.86	4.67	0.45	−1.20
9 223 000	Hams Fork Below Pole Creek, Near Frontier, WY. (west)	9.38	9.70	3.48	−0.33	−0.29
9 312 600	White River Bl Tabbyune C Near Soldier Summit, UT. (west)	2.34	2.46	1.42	0.43	0.09
9 378 170	South Creek Above Reservoir Near Monticello, UT. (west)	0.05	0.05	0.05	1.65	3.90

Note: CO = Colorado; UT = Utah; WY = Wyoming; LAT_GAGE = Latitude of a streamgauge; LONG_GAGE = Longitude of a streamgauge.

Table 2. Correlation coefficients between annual q7 time series of different stations. Only 90 % statistically significant estimates are shown.

Station ID	9 034 900	9 066 200	9 306 242	9 081 600	9 035 800	9 065 500	9 047 700	9 066 300	9 035 900	9 107 000	9 352 900	9 183 500	9 210 500	9 223 000	9 312 600	9 378 170	9 034 900
9 066 000																	
9 034 900																	
9 066 200	0.48																
9 306 242																	
9 081 600	0.57		0.49														
9 035 800	0.41			0.51	0.37												
9 065 500			0.60		0.40												
9 047 700	0.60			0.48		0.47											
9 066 300			0.46		0.40		0.41	0.47									
9 035 900	0.42					0.50		0.47	0.51								
9 107 000					0.42				0.45								
9 352 900			0.48		0.61				0.35		0.54						
9 183 500				0.56		0.47											
9 210 500	0.48			0.55		0.54		0.62		0.49							
9 223 000				0.40				0.50	0.53					0.58			
9 312 600	0.60				0.37	0.52		0.59		0.44			0.39	0.66	0.59		
9 378 170				0.60									0.65			0.38	

Table 3. Correlation coefficients between JJA q7 time series of different stations. Only 90 % statistically significant estimates are shown.

Station ID	9 034 900	9 066 200	9 306 242	9 081 600	9 035 800	9 065 500	9 047 700	9 066 300	9 035 900	9 107 000	9 352 900	9 183 500	9 210 500	9 223 000	9 312 600	9 378 170	9 034 900
9 066 000																	
9 034 900	0.73																
9 066 200	0.81	0.78															
9 306 242	0.64	0.47	0.47														
9 081 600	0.74	0.48	0.78	0.58													
9 035 800	0.61	0.61	0.70	0.58	0.76												
9 065 500	0.87	0.71	0.86	0.61	0.89	0.78											
9 047 700	0.78	0.73	0.78	0.41	0.59	0.56	0.76										
9 066 300	0.83	0.77	0.85	0.48	0.61	0.65	0.74	0.72									
9 035 900	0.87	0.74	0.80	0.54	0.75	0.62	0.83	0.80	0.83								
9 107 000	0.82	0.48	0.78	0.61	0.92	0.62	0.90	0.67	0.65	0.77							
9 352 900	0.68	0.57	0.60	0.55	0.62	0.57	0.69	0.53	0.57	0.47	0.69						
9 183 500	0.73	0.61	0.77	0.63	0.80	0.77	0.79	0.53	0.60	0.60	0.71	0.67					
9 210 500	0.63	0.44	0.47	0.58	0.37		0.45	0.58	0.49	0.61	0.49	0.42	0.50				
9 223 000	0.68	0.49	0.50	0.76	0.54	0.56	0.59	0.60	0.55	0.65	0.56	0.54	0.60	0.87			
9 312 600	0.70	0.44	0.71	0.72	0.81	0.67	0.72	0.62	0.68	0.74	0.80	0.52	0.72	0.68	0.74		
9 378 170	0.72	0.70	0.73	0.48	0.69	0.62	0.78	0.60	0.49	0.58	0.62	0.60	0.86	0.43	0.49	0.52	

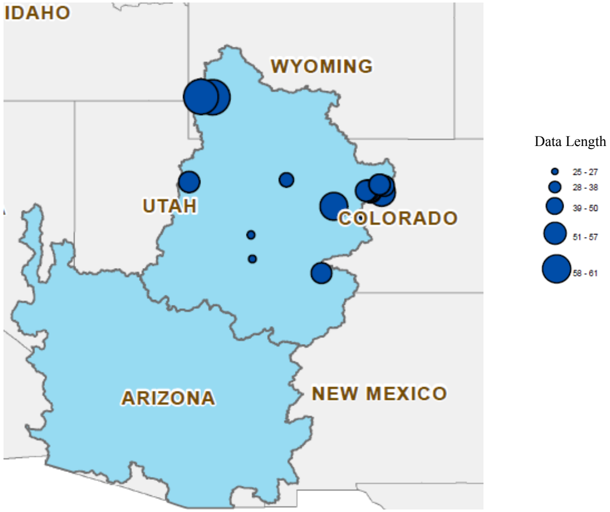

Figure 1. 17 undisturbed stream gauge locations in the Upper Colorado River Basin and stream flow data lengths (in years).

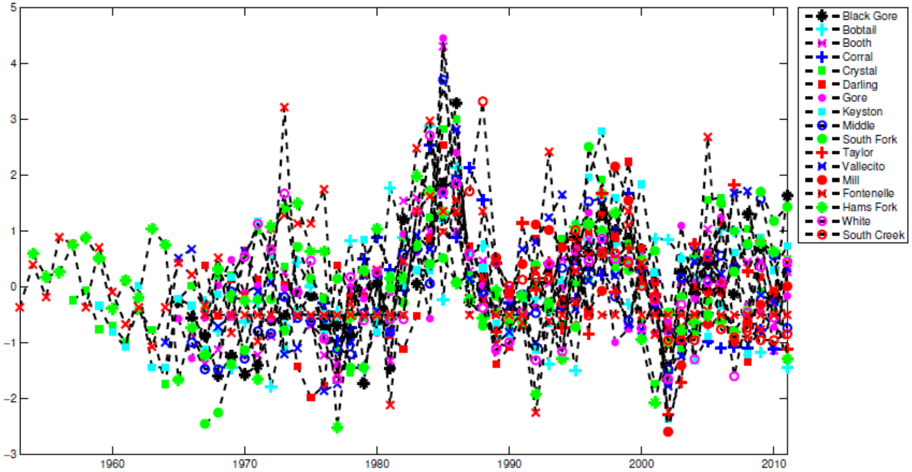

Figure 2. Standardized annual variation of q7.

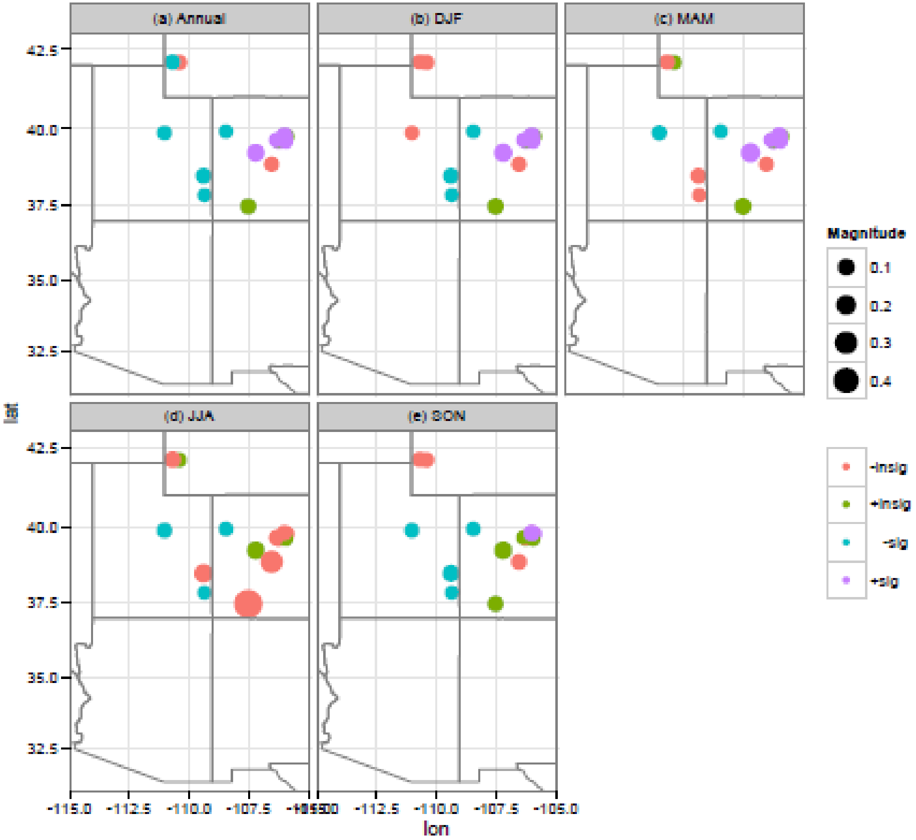

Figure 3. Monotonic trends for q7 for each stream-gauge location **(a)** annual, **(b)** DJF, **(c)** MAM, **(d)** JJA, **(e)** SON. Color bubbles indicate location of each station, sign and significance of the trend estimates. 90 % significant levels are used. The size of the bubble is proportional to the magnitude of the trend.

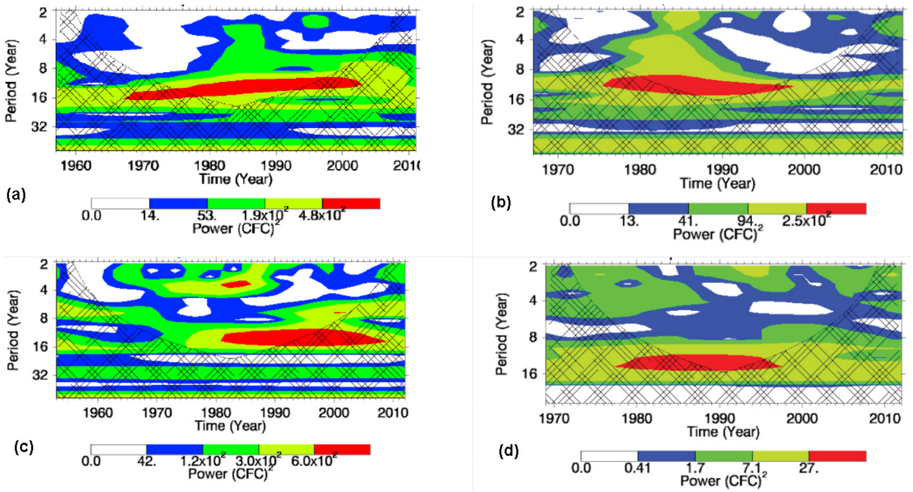

Figure 4. Example periodicity of low flow magnitudes. Wavelet power spectrum for **(a)** annual q7 time series for Crystal station (east), **(b)** JJA q7 time series for South Fork station (east), **(c)** JJA q7 time series for Fontenelle station (west), **(d)** SON q7 time series for White station (west).

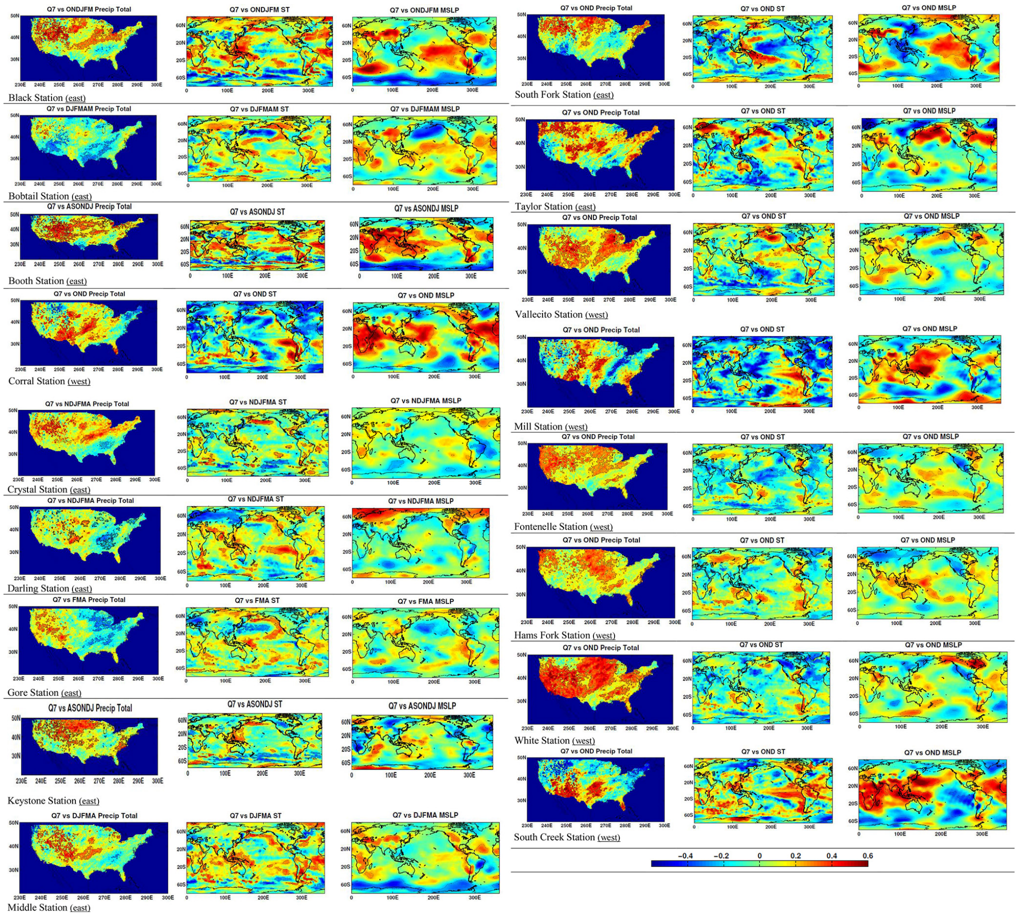

Figure 5. Correlations between annual q7 with climate data (95 % significant regions are marked by dotted contours).