Chapter 10

THE TRANSBOUNDARY SETTING OF CALIFORNIA'S WATER AND HYDROPOWER SYSTEMS

Linkages between the Sierra Nevada, Columbia, and Colorado Hydroclimates

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Abstract Climate fluctuations are an environmental stress that must be factored into our designs for water resources, power, and other societal and environmental concerns. Under California's Mediterranean setting, winter and summer climate fluctuations both have important consequences. Winter climatic conditions determine the rates of water delivery to the state, and summer conditions determine most demands for water and energy. Both are dictated by spatially and temporally structured climate patterns over the Pacific and North America. Winter climatic conditions have particularly strong impacts on hydropower production and on San Francisco Bay/Delta water quality.

It is thus noteworthy that precipitation from winter storms in California is more variable than in neighboring regions. For example, annual discharge from the Sacramento–San Joaquin system has a coefficient of variation (standard deviation/mean) of 44% compared to 19% in the Columbia Basin and 33% in the Colorado Basin. Also, in California, multiyear droughts occur more often than would be expected by chance, but wet years do not exhibit such persistence. A crucial aspect of California's climate stresses is that they influence conditions over broad spatial scales. Climate patterns that cause the state's climatic fluctuations typically reach well beyond its boundaries. This breadth affects California because much of the energy and water used here is supplied by distant parts of the state as well as from the Northwest and Southwest. When dry winters occur in the Sierra Nevada, they also tend to occur in the Columbia and Colorado Basins.

These regional scales, coupled with California's reliance on resources from an especially broad region, including power from the Columbia and Colorado Basins and water from the Colorado, make the state especially vulnerable to climate fluctuations. These vulnerabilities are likely to grow as the population and demands for resources in the region continue to grow.

1. INTRODUCTION

Environmental stresses such as climate fluctuations have the potential to cause ever-greater impacts on the western United States as the population grows. From 1990 to 2000, the population of the 11 western conterminous United States increased by 19.7%, from 51.2 to 61.3 million residents. Over the same period, the number of people in California (the most populous state in the nation) rose by nearly 14%—from about 29.8 million to about 33.9 million residents (United States Census data 2000). Among the multitude of stresses threatening, and associated with, this rapidly growing population, climate variations have large impacts on societal and ecological structures because they determine the amount of resources, such as water, supplied to the region. Furthermore, the stresses placed upon one region can affect conditions in others, partly because water and energy are traded or transferred across state and watershed boundaries.

As can be argued for a global scale, in the western United States there are compelling reasons to consider environmental and societal stresses at the scale of large watershed systems. In many cases, a region's populace depends upon processes and human activities within a watershed for substantial portions of its water supply, electrical power, ecological habitat, transportation, and recreation. Consequently, recent applied science programs to study and organize multidisciplinary climate and environmental information for the western United States have structured their efforts around watersheds; e.g., the U.S. Geological Survey's Place-Based Studies Program (http://access.usgs.gov/) and the National Oceanic and Atmospheric Administration Office of Global Programs (NOAA-OGP) Regional Integrated Science Assessments (http://www.ogp.noaa.gov/mpe/csi/risa/). California's largest watershed is the collection of river drainages from the west slope of the Sierra Nevada that combine to form the Sacramento and San Joaquin Rivers. These large rivers converge at the San Francisco Bay Delta and supply much of the state's water. This overall watershed and rivers system is termed the Sierra watershed in this chapter.

Hydroclimatic linkages of the Sierra to two other large watersheds, the Columbia River Basin (Pulwarty and Redmond 1997; Hamlet 2002, this volume) and the Colorado River Basin (Diaz and Anderson 1995; Harding et al. 1995; Lord et al. 1995), are analyzed in this study. These three watersheds are shown on the map in Figure 1, and the annual discharge (natural flow estimates) is plotted in Figure 2. Each of these systems is highly managed (Hamlet 2002, this volume; Lord et al. 1995), and in each, climate variability is recognized as a major stress (Roos 1991, 1994; Pulwarty and Redmond 1997; Hamlet 2002, this volume; Diaz and Anderson 1995; Harding et al. 1995; Lord et al. 1995; California Department of Water Resources 1998).

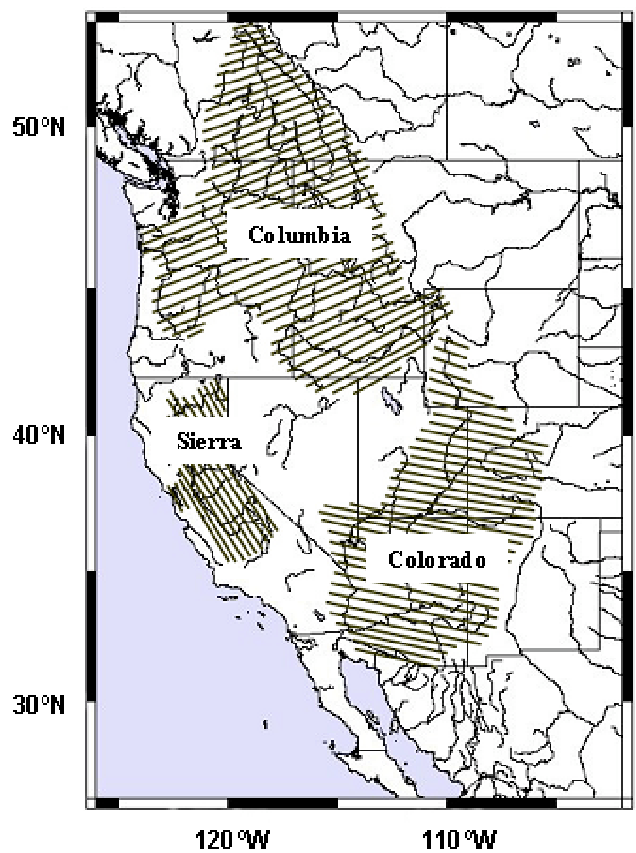


Figure 1. Columbia, Sierra, and Colorado watersheds.

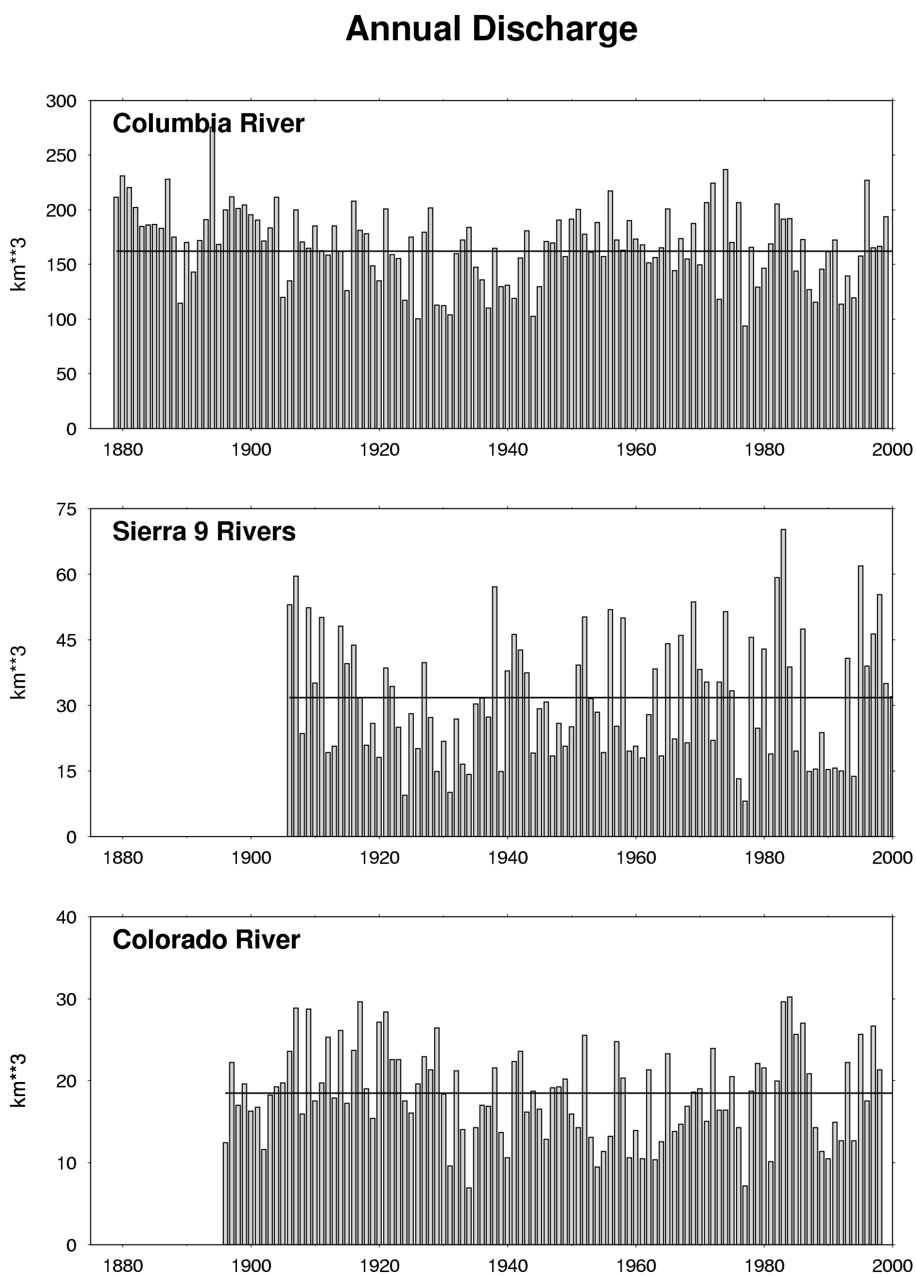


Figure 2. Water-year natural river-discharge totals (cubic kilometers) for the Columbia River at The Dalles, the Sierra watershed (nine largest rivers draining the west slope of the Sierra Nevada), and the Colorado River at Lees Ferry. Horizontal lines indicate 1906–99 mean (1906–99) discharge.

California's water and power supplies are intimately linked to the hydroclimates of all three watersheds. In an average year, California receives about 200 million acre feet (hereafter MAF; 1 MAF = 1.234 km^3 of water) of precipitation, of which only 71 MAF is left after evaporation and transpiration to form runoff. About 42 MAF of this runoff is used for nonenvironmental (agricultural or urban) consumption. Even within the state, water supplies link different regions. Approximately 75% of the state's runoff occurs north of San Francisco Bay, while 72% of nonenvironmental consumption occurs south of San Francisco Bay, supplied by massive federal and state water storage and conveyance systems (California Department of Water Resources 1998). These wholesale within-state water transfers affect water quality and ecosystems as well as water users. Water quality in San Francisco Bay, indicated by May monthly salinity anomalies at Suisun Bay, is very strongly correlated ($r = 0.96$) with freshwater flows from the Sierra watershed as shown in Figure 3. However, also illustrated in Figure 3 are freshwater withdrawals from the San Francisco Bay Delta southward to the San Joaquin Valley or Southern California. These exports have increased over the last few decades and have contributed to water quality and estuarine degradation in the bay and delta (Peterson et al. 1995; Knowles 2002; Knowles et al. 2002). Withdrawals from the delta are usually greatest in July and August and least in January and February (Knowles et al. 2002). Interestingly, and perhaps important from water and energy resources perspectives, is that withdrawals on the Columbia system are greatest in winter and least in summer (Hamlet 2000, this volume). These exports are determined by demand, supply, and perhaps the timing of the winter storm season, and thus exhibit a complex relationship to freshwater flows. From outside the state, during recent years California has imported about 5.4 MAF of water, most of it from the Colorado River and some from Oregon (California Department of Water Resources 1998). Also, about 1.2 MAF flows from California to Nevada from the east side of the Sierra Nevada. In summary, California depends upon the Colorado River to supply approximately 12% of its 42.6 MAF annual developed, nonenvironmental water supply. California is currently scrambling to assemble a workable plan to live within its legal yearly entitlement from the Colorado River of 4.4 MAF (Newcom 2002). Thus, California's water supplies include disparate sources, both within and beyond its boundaries, with particularly important linkages to the Colorado Basin.

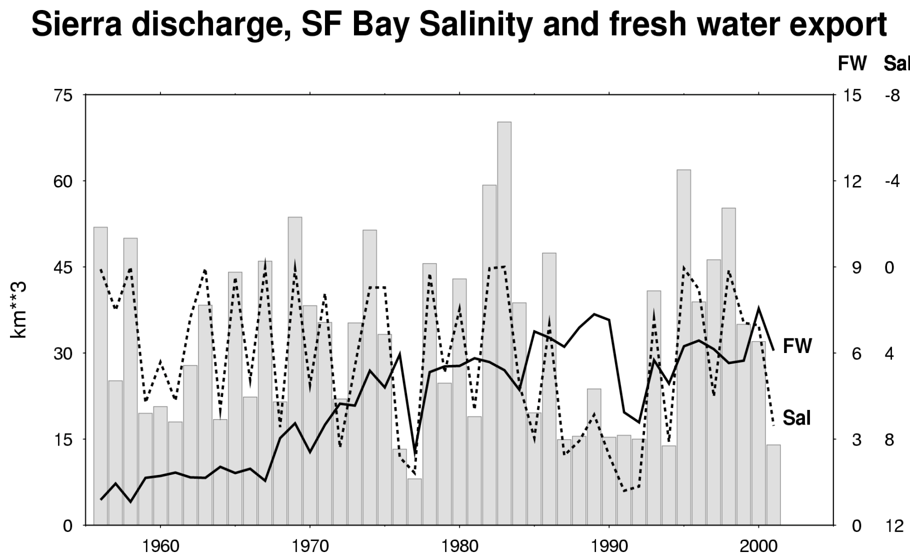


Figure 3. Sierra discharge (cubic kilometers) (bars), San Francisco Bay May salinity anomalies [per mille] in Suisun Bay (dotted line) and freshwater export (cubic kilometers) southward from the San Francisco Bay Delta (solid line). Salinity is estimated from the advection/diffusion model of Knowles (2002).

Meanwhile, California's electrical consumption, approximately 230,000 gigawatt-hours (GWh) per year, is approximately 40% of the total consumption of the 11 western states (Fisher and Duane 2001). This situation developed while annual consumption over the 11 western states increased from 350,000 GWh in 1977 to nearly 570,000 GWh in 1998, an increase of 63%. California's electrical system is closely connected to that of the 11 western states, and nearly 20% of California's electricity is imported, about equally from the Northwest and the Southwest regions of the United States (Fig. 4; California Energy Commission data). These imports are a necessary part of California's energy system today, because California/Mexico peak electrical demand is approximately 55,000 megawatts (MW) and California's electrical generation capacity is only about 44,000 MW. California's consumption increased from 160,000 GWh in 1977 to 230,000 GWh in 1998, an increase of 43% (Fig. 4). The western region has a total capacity of 133,000 MW and a peak demand of approximately 130,000 MW (Fisher and Duane 2001). Important from a seasonal climate perspective is that in California, peak demand in summer is usually nearly 50% higher than it is in winter, while in the Pacific Northwest, peak demand in winter is about 20% higher than it is in summer. For the combined western states, peak demand is approximately 10% higher in summer than in winter, evidently because of the increased load caused by air conditioning, pumping water, and other seasonal activities. Peak demand in the western region has increased from 84,000 MW to over 130,000 MW from 1982 to 1998; this constitutes more than a 50% increase in two decades. Hydroelectric power generation within California averages about 35 GWh, about 15% of total electrical generation (Fig. 4). Notice, in Figure 4 and in Table 1, that year-to-year variations in hydropower generation in the Sierra Nevada have closely followed the year-to-year availabilities of Sierra discharge with a correlation of approximately 0.9. The importation of power to California, by contrast, has generally followed year-to-year fluctuations in the flow of the Columbia River, especially prior to 1995 ($r = 0.58$). The amount of imported electrical energy was particularly low in 2000, when the Columbia River Basin, along with most of the northwestern United States, was very dry. Thus California's electrical power situation typically responds to the hydroclimates of both river basins, as well as to the hydropower sources of the Colorado River system. Indeed, California's recent power crisis, during which electricity costs were driven up catastrophically in the summer of 2001, developed in part because of lower than expected hydropower production in the Columbia Basin due to prolonged dry conditions in the Northwest (e.g., http://www.sfgate.com/energy/).

Because of these interdependencies, a year during which any one of the three watersheds is drier than normal poses potential problems for California. Years in which two or more of the watersheds are dry are particularly threatening. These threats become especially problematic if neither of the remaining watersheds is wet enough to permit compensatory adaptations in California's water or, especially, power systems. Conversely, years in which one basin is wet and one of the others is dry may have compensating benefits. Droughts, as well as floods, are clearly normal facets of the modern climate, although they have posed particularly severe resource-management problems during recent decades (Roos 1994; Betancourt 2002; McCabe et al. 2002; Namias 1978, National Research Council [NRC] 1999). High-resolution paleoclimate measures indicate that the western region has enjoyed wet spells but has also suffered severe sustained drought during the last several centuries (Meko et al. 1995; Stahle et al. 2001; Meko et al. 2001; McCabe et al. 2002). Thus, in this chapter we attempt to clarify these linkages by investigating how high and low river discharges in the Sierra watershed have historically related to (coincided with) those in the Columbia and Colorado Rivers and how these relationships are determined by climate variability.

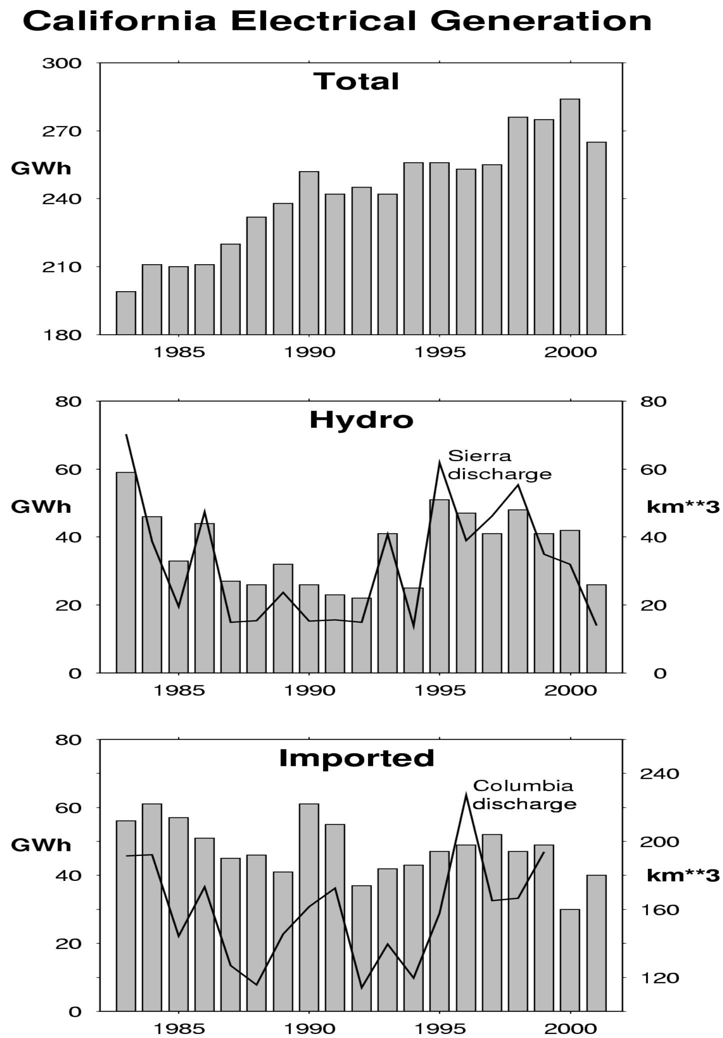


Figure 4. (*a*) Total generated electricity used in gigawatt-hours (GWh) in California (upper), (*b*) hydroelectric energy generated (GWh) in California (middle), and (*c*) net imported electrical energy used (GWh) in California (lower). For comparison, Sierra watershed water-year discharge (cubic kilometers) and Columbia River water-year discharge (cubic kilometers) are also plotted (solid lines) on the middle and lower panels.

Table 1. Correlations among annual hydroelectric generation totals and correlations between annual hydroelectric generation and annual discharge in the western United States, 1976-1994.

(Hydroelectric data from Western Area Power Administration)

	hydro-electric generation regions				*watersheds*		
	Pacific NW	California-Nevada	Ari-zona-New Mexico	Rocky Mtns	Columbia River	Sierra Watershed	Colorado River
Pacific NW		0.27	-0.08	0.19	0.92		
Califor-nia-Nevada			0.33	0.76		0.88	
Arizona New Mexico				0.73			0.54
Rocky Mtns.							0.80

2. DATA

Natural discharge estimates are analyzed for the Columbia River at The Dalles, by using data from the U.S. Army Corps of Engineers, for the Colorado River at Lees Ferry, from annual reports of the Upper Colorado River Commission, and for the nine largest rivers (Upper Sacramento, Feather, Yuba, American, Stanislaus, Tuolumne, Merced, Upper San Joaquin, and Kings Rivers) draining the west slopes of the Sierra Nevada, based on data from the California Department of Water Resources. Discharge measurements from hundreds of additional gages around the conterminous United States, selected for their relative lack of human influences (Slack and Landwehr 1992), also are analyzed to provide regional hydrologic contexts for the behaviors of the three large watersheds considered here. Monthly precipitation totals for United States climate divisions (Karl and Knight 1985) from the National Climatic Data Center are used to characterize precipitation inputs to each of the three watersheds. For the Columbia watershed, the Canadian sector that comprises the upper part of the basin is not included. Daily precipitation from hundreds of cooperative and first-order stations over the conterminous western United States (Eischeid et al.

2000) were employed to characterize the variability within and between watersheds across the region. Monthly gridded 700 millibar (mb) height fields over the Northern Hemisphere obtained from the NOAA National Center for Environmental Prediction are analyzed to identify large-scale atmospheric circulations associated with the hydroclimatic variations. Finally, annual electrical energy generation and usage data were obtained from the Western Area Power Administration and the California Energy Commission.

3. RUNS OF HIGH AND LOW DISCHARGE

Water and power users in the three western river systems must contend with the year-to-year variations of flow in the three rivers, as illustrated by their time histories shown in Figure 2. For example, flows in the California Sierra have fallen as low as 25% (water year 1977) of the historical mean and have been as high as 221% (water year 1983) of the historical mean. The variability of the Sierra watershed is particularly high among the three watersheds analyzed in this chapter. Its coefficient of variation of the annual discharge is 0.44, compared to 0.19 for the Columbia and 0.33 for the Colorado (Table 2). The high Sierran variability is a reflection of a regional pattern of high coefficients of variation across the Southwest (Fig. 5). The Columbia watershed, like most rivers in the Northwest, experiences much less variability. The Colorado watershed drains parts of both the Southwest (with high variability) and the interior Northwest (with low variability), and thus as a whole is moderately variable. Also, the area of the Sierra watershed, at approximately 140,000 km^2, is less than one-fourth the size of the Columbia watershed (approximately 617,000 km^2) or the Colorado watershed (approximately 242,000 km^2). Consequently, there is not great opportunity for one portion of the Sierra drainage to compensate for the extremes that occur in another portion of the watershed (Cayan 1996).

Table 2. Annual discharge statistics, 1906–1999.

	_ *[km^3]*	_ *[km^3]*	*C.V*	max *[km^3]*	min *[km^3]*
Columbia	162.4	31.0	0.19	236.9 *(1974)*	93.9 *(1977)*
Sierra	31.8	14.1	0.44	70.2 *(1983)*	8.1 *(1977)*
Colorado	18.6	5.7	0.33	30.2 *(1984)*	6.9 *(1934)*

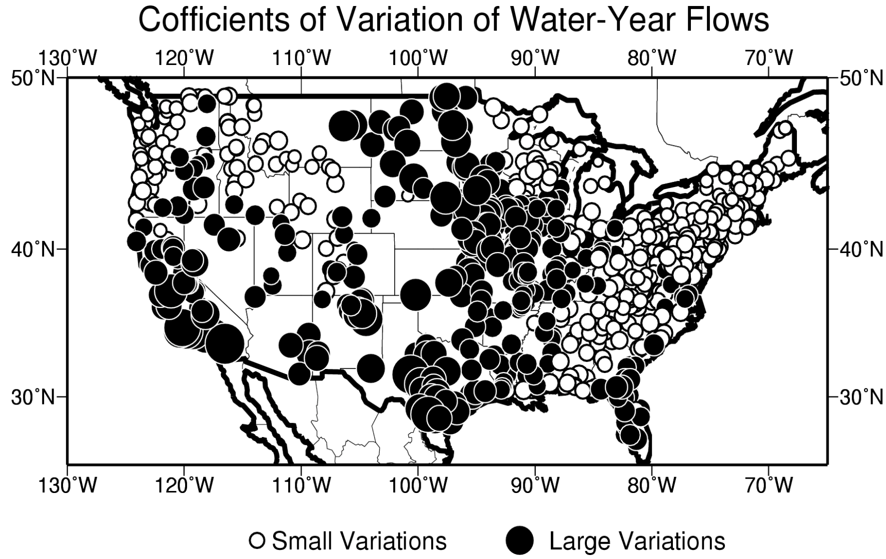


Figure 5. Coefficients of variation of annual discharges in streams in the conterminous United States for the periods of record at each gage. Circle radius is proportional to the magnitude of the coefficient. Values less than 0.37 and greater than 0.37 are plotted as open/filled circles, where 0.37 is the median value from all the gages shown.

Precipitation, which fosters this discharge variability in the three watersheds, falls over differing seasons and, especially, over differing fractions of the water year. The duration of the season over which the major fraction of annual total precipitation accumulates is particularly short in California, in accord with its Mediterranean precipitation regime. Figure 6a shows that L67, defined here as the number of days required to accumulate 67% of the mean annual precipitation, is a relatively brief period in the California region. L67 is calculated by using daily long-term mean precipitation data (Eischeid et al. 2000) to identify the period of the year, regardless of starting day, that accumulates 67% of the annual mean precipitation. L67 ranges from about 90 to about 120 days in California. In contrast, the wet seasons measured by L67 are longer (120 to 220 days) in the other two basins. This means that the Sierra watershed accumulates its yearly water supply in a relatively short time, on average. The narrow seasonal window that provides precipitation for California may also contribute to the high variability of the state's precipitation and runoff. The shorter the period within which a region typically accumulates its annual precipitation supply, the more vulnerable it will be to climate fluctuations. When the wet season is short, there are fewer chances to offset dry spells, should they occur during the core precipitation season. This is illustrated, for example, by the relative magnitude of variability, indicated by the coefficient of variation (standard deviation/mean) of each year's cumulative precipitation over each station's L67 period (Fig. 6b). The coefficient of variation is high (30–60%) throughout California compared to the other regions of the western United States. These levels of precipitation variability conform to the general pattern of streamflow variability (Fig. 5) across the western United States, in which the lowest relative variability is in the Pacific Northwest and the greatest variability is in the Southwest and especially California. Notably, in a separate analysis of the streamflow variability, we found no tendency for this pattern, or the absolute values of coefficients of variation, to depend on the sizes of the river basins considered.

Reservoir storage is used in each of the three watersheds to moderate this variability. The amounts of storage in the three river systems are quite similar, with 50, 32, and 60 MAF (60, 49, and 74 km^3) of storage in the Columbia, California, and Colorado systems, respectively. In terms of annual flow volume, however, these storages are remarkably dissimilar, at 30%, 154%, and 397% of average annual discharge, respectively. Thus, while the Colorado is distinguished by low variability, it has relatively little storage. The Colorado has moderately high variability but it has a large storage capacity. The Sierra system has high variability and a modest amount of reservoir storage.

Overall, there is little persistence of a given year's anomalous discharge to that of the next year. The 1-year autocorrelations of the Columbia, Sierra, and Colorado annual discharges are 0.06, 0.08, and 0.24, respectively. However, the annual discharge series (Fig. 2) for the three watersheds contain decadal to multidecadal variations. Spectral analysis, using the multitaper method (Mann and Lees 1996), identifies these low-frequency variations as marginally significant in the Colorado discharges, more convincingly significant in the Sierra, and strongly significant in the Columbia River series. For many concerns, the associated multiyear runs of high or low flows have greater societal and ecological impacts than isolated extreme years.

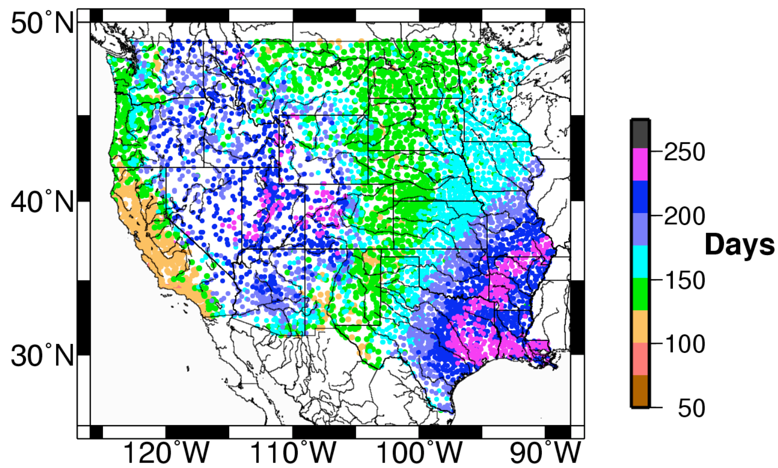
To investigate further, an analysis of "runs" of high or low extremes was conducted. In this chapter, we adopt relatively weak criteria for identifying wet spells and droughts: In the present analysis, extreme events are defined as years in which the annual discharge is in the upper/lower third or upper/lower sixth of its observed distribution. This analysis was performed by tallying the number (m) of above-high-threshold and below-low-threshold flows within each successive N-year interval of the flow series. In the experiment discussed here, the two thresholds considered were the upper and lower sextiles of the annual discharge series, although the upper/lower terciles and above/below median also were examined with qualitatively similar results. The interval length N = 10 yr was considered. The resulting distribution of m's was compared with those from a Monte Carlo experiment in which the annual discharge series were shuffled randomly over 1,000 independent trials (Fig. 7). As was suspected from visual inspection and the spectral analysis, this analysis demonstrates that anomalously low and sometimes high-discharge years cluster in time, more so than can be explained by chance. For example (Fig. 7), while the random series would on average produce only six 10-year intervals containing four or more lowest sixth flow volumes, the observed Sierra discharge series produced 17 such 10-year intervals in the 1906–99 historical record (Table 3). The low Sierra discharge sequences fell into two main episodes: beginning in the late 1920s and beginning in the mid-1980s through the early 1990s. The number of 10-year intervals with "runs" of 4 or more years of high flows is not as unusual as the number of low-flow runs, except for the Colorado River (Fig. 7).

Table 3. 10 *yr* intervals with 4 or more extremely high or extremely low annual discharge totals. Extremes are highest and lowest 16 years between 1906 and 1999. Years listed are beginning year of each 10-year interval.

Columbia		***Sierra***		***Colorado***	
high 10	*low 10*	*high 10*	*low 10*	*high 10*	*low 10*
1965	1921	1906	1924	1906	1952
1967	1922	1907	1925	1907	1953
1968	1923		1926	1908	1954
1969	1924		1927	1909	1955
1970	1925		1928	1911	1956
1971	1926		1929	1912	1957
	1928		1930	1913	1958
	1929		1931	1914	1959
	1985		1982	1977	1985
	1986		1983	1978	1986
	1987		1984	1979	1987
			1985	1980	1988
			1986	1981	1989
			1987	1982	
			1988	1983	
			1989		
			1990		

a. L67: Time (days) to accumulate 67% of annual total precip

Mean of length of record, daily CO-OP and 1st order stations



b. Coefficient of Variation (σ/μ) of L67

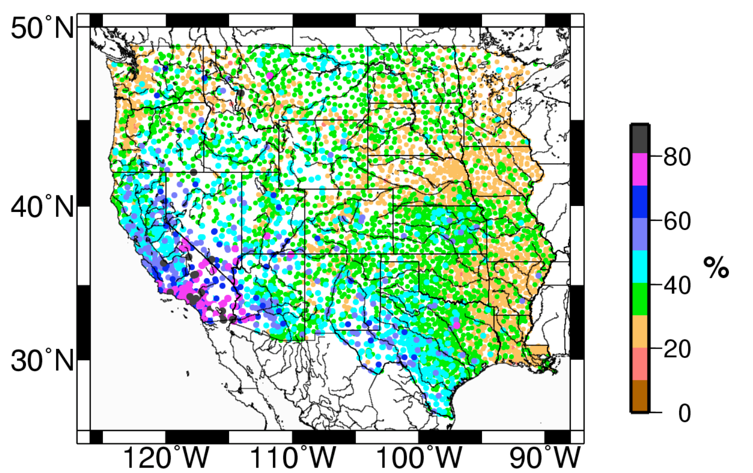


Figure 6.(*a*) Number of days (L67) required to accumulate 67% of the annual climatological total precipitation, calculated from long-term daily mean precipitation over the entire record available at each station. The beginning of the L67 "season" is the day for which L67 precipitation accumulation is at its minimum. The dot size becomes darker (see shading scale) and larger as L67 decreases. (*b*) Coefficient of variation (standard deviation/mean) of accumulated precipitation over the climatological L67 period of each year. The dot size becomes darker (see shading scale) and larger as the coefficient of variation increases.

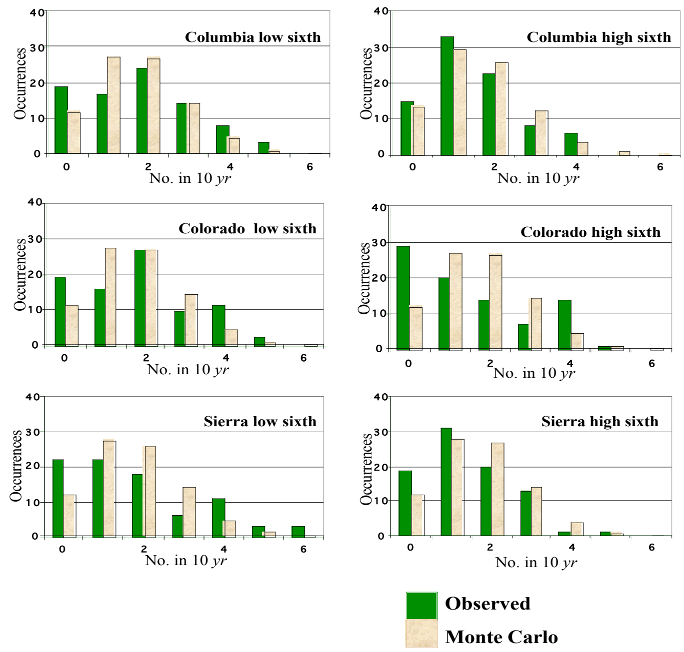


Figure 7. Observed (black) vs. Monte Carlo (gray) simulated occurrences of m years (x-axis) out of 10 years when annual discharges were in the lowest (upper) and highest (lower) sixth of the long-term flow distributions for the Columbia, Sierra, and Colorado watersheds.

4. REGIONAL CONNECTIONS OF HIGH AND LOW DISCHARGE

Although the climates of the Columbia, Sierra, and Colorado Basins differ from each other, their water-year hydrologic variations are often correlated (Cayan 1996; Dettinger et al. 1998). Figure 8 shows average discharge anomalies (as *t* scores) at U.S. Geological Survey stream gages during years with high (left side panels) and low (right) discharge in the three watersheds. High/low years are defined as those whose annual discharge was in the upper/lower third of its observed 1906–99 distribution. Each composite has the strongest anomalies in and near the targeted watershed, but as importantly, each has significant anomalies that spread on a regional scale, well beyond the watershed. Interestingly, some strong anomalies extend well to the east; e.g., when heavy flows occur in the Sierras and in the Colorado River system, heavy flows also occur in rivers in the northern Great Plains and western Midwest. When the Colorado River experiences high or low flows, rivers over the Pacific Northwest and along a broad swath of the East Coast also tend to have low or heavy (opposite) flow statuses. Examination of the discharge series reveals several cases when the Colorado and Columbia Rivers are in opposite phase extremes (Table 4). There is a lesser tendency for out-of-phase structure for the Sierra vs. the Columbia River systems, and very little evidence for the Sierras vs. the Colorado River systems. The composite streamflow patterns are roughly symmetric over the western United States when considering high- versus low-flow years in the three watersheds.

However, an important distinction, which bears on the region's water and hydropower resources, is that the regional streamflow patterns associated with Columbia and Colorado low-flow years are more extensive than the patterns in the high-flow years. Notably for California's water and power resources, when the Columbia River is drier than normal, low flows occur in rivers extending southward into Northern California. Low-flow anomalies associated with dry years on the Colorado extend westward into most of California. The high-flow patterns associated with both of these basins are more constricted and not as strong over California.

The association between high and, especially, low flows in the three watersheds can also be seen by the numbers of co-occurring years with high and low annual discharges in the three river systems (Table 4). In each pair, especially for the Sierra-Colorado pair, high-high and low-low flow combinations predominate, and high-low or low-high combinations are relatively uncommon. These contingencies stand out as highly significant when compared to Monte Carlo experiments matching extreme-year pairings in 1,000 randomly shuffled versions of the three discharge series. The Monte Carlo exercise indicates that 7.6 ± 2.0 low Sierra/low Columbia flow years and 9.2 ± 2.2 low Sierra/low Colorado flow years would occur if the discharge series were randomly and independently arranged, while the observed series produced 13 and 16 such occurrences, respectively. High/high flow years are similarly accentuated in the observed series, while high/low and low/high coincidences across the pairs of basins occurred less often than chance would have them. Finally, if we consider cases where all three basins have low flows or all three have high flows, the Monte Carlo exercise produces 2.3 ± 1.3 and 1.1 ± 1.0 such years by chance, while the observed record has six low/low/low years (1931, 1939, 1977, 1988, 1992, 1994)[1] and four high/high/high years (1907, 1916, 1965, 1983). Thus, the three western

[1] 2001 was not included in the present analysis, but would qualify as another low/low/low year.

watersheds share hydrologic extremes much more than would be expected by chance.

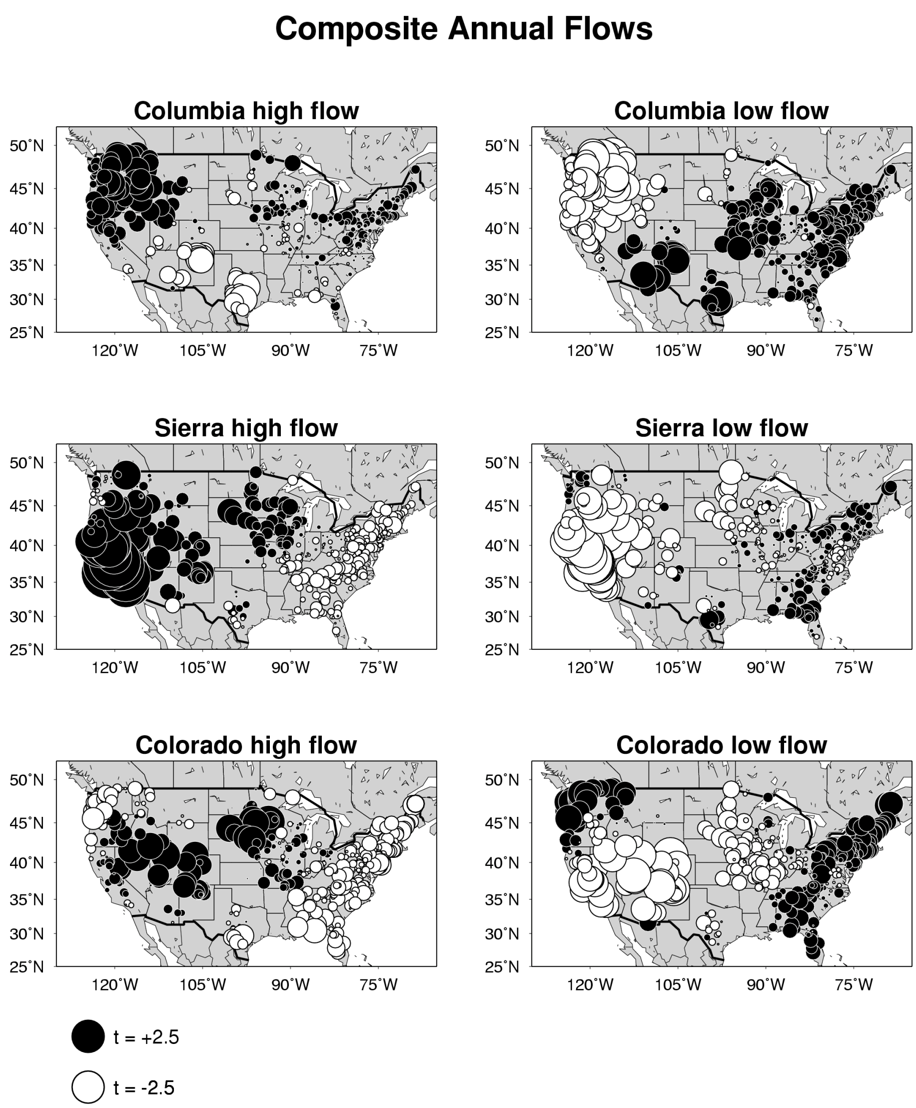


Figure 8. Average annual-discharge anomalies, as *t* statistics, for years when the Columbia, Sierra, and Colorado discharges exceeded their average discharges by 0.7 standard deviations or more (left-hand maps) or were less than their average by 0.7 standard deviations or more (right-hand maps). The filled circles indicate anomalously high flows, and open circles indicate anomalously low flows associated, on average, with flow anomalies in the three study watersheds.

Table 4. Co-occurrences of high (*h*) and low (*l*) annual discharge for Columbia, Sierra and Colorado watershed pairs. Anomalies ≥ 0.7 □, ≤ -0.7 □ define high and low discharge, respectively. From 1906–1999 data.

		Sierra				Sierra				Columbia	
		h	*l*			*h*	*l*			*h*	*l*
Columbia	*h*	8	3	Colorado	*h*	13	4	Colorado	*h*	7	4
	l	2	13		*l*	2	16		*l*	5	7

5. CLIMATE PATTERNS

Mechanisms that produce these watershed-to-watershed wet and dry coincidences are orchestrated by large-scale atmospheric circulations and climatic regimes (Namias 1978; Dettinger et al. 1998). In each of the three basins, the factor having the greatest impact on annual discharge is the winter pattern, as indicated by the winter precipitation anomaly (Fig. 9). Excesses or deficits of precipitation that build up during high- and low-flow years (and that ultimately generate those high and low flow rates) tend to begin in fall. In the Columbia watershed, precipitation excesses and deficits associated with high- and low-flow years are largely (and most reliably) established by about January. In the Sierra watershed, precipitation excesses and deficits typically (on average) are established by excesses and deficits that begin in late fall and continue to accumulate well into March. Deficits and, especially, excesses in the Colorado watershed are associated with precipitation anomalies from almost any month, either in the preceding or concurrent water year.

These differences in the seasons that ultimately contribute most to wet or dry years in the three watersheds result in differences in how well, and when, water managers in the watersheds can anticipate the eventual water-year discharge. Figure 10 compares the amount of information available about the eventual January–September and April–September discharges (on average) from knowing the accumulated precipitation to date in each of the three watersheds, as a function of the month of the water year. In this case, the amount of information is measured in variance of the January–September and of the April–September discharge explained by the accumulated precipitation from the beginning of the water year to a given

[2] 2001 was not included in the present analysis, but would qualify as another low/low/low year.

month. Precipitation is the climate division monthly precipitation averaged over each watershed. (For the Columbia River, the watershed region included was only the portion of the basin that lies within the United States.) Clearly, a water or hydropower manager in the Columbia watershed—by this measure—has an advantage, knowing relatively more about how wet or dry a given year will be, until February. In February, the manager in the Sierra is finally able to operate on equal footing. Thereafter, because of the more severely Mediterranean, wet-winter-only climate of the Sierra, compared to the Columbia and Colorado, the Sierran manager has a clearer idea of what the water-year total resource will be. A manager on the Colorado appears to be at an information disadvantage throughout the year, although there may be superior measures of precipitation than the divisional averages employed here. In each basin, a little more variance is explained for the January–September discharge than for the April–September discharge, but the month-by-month increases in variance explained for both of these discharge seasons are nearly the same.

The feature that provides the spatial coherence in the anomalously wet or dry precipitation patterns of the three watersheds is the atmospheric circulation. In winter, it is not unusual to find broad anomalous low- or high-pressure centers over the Pacific–North America sector that reflect the presence or absence of storm activity in one or more of the watersheds (Fig. 11). While prominent climate modes (El Niño/Southern Oscillation [ENSO] and the Pacific Decadal Oscillation [PDO]; Mantua et al. 1997; Gershunov et al. 1999) play strong roles in delivering wet or dry winters to the Columbia watershed, they are not very reliable determinants of wet or dry conditions in either the Sierra or the Colorado watershed (Tables 5 and 6). In the Columbia Basin, the La Niña phase of ENSO and the cool phase of the PDO favor high flows, and the El Niño phase of ENSO and the warm phase of the PDO favor low flows. Interestingly, though, all of the cases having the combination of higher than normal annual discharge on the Columbia River and lower than normal annual discharge on the Colorado River occurred during the PDO cool phase episode between 1947 and 1976.

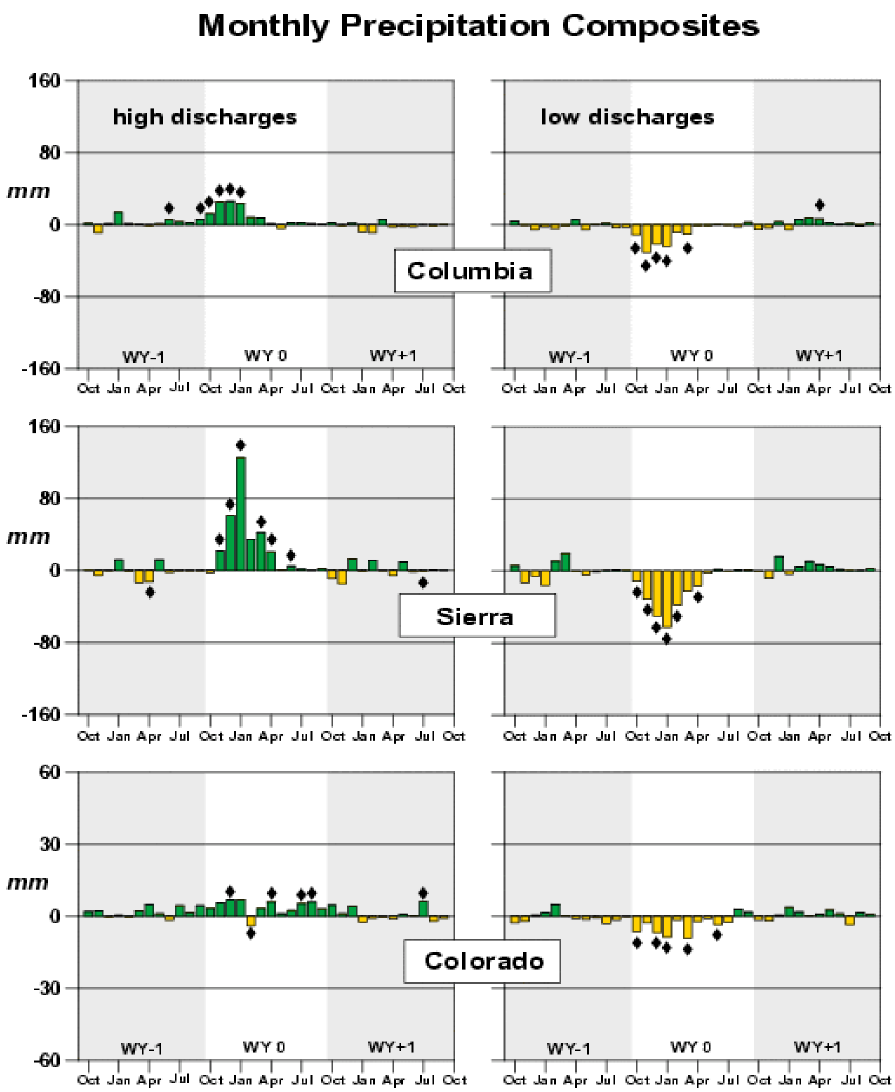


Figure 9. Average monthly precipitation anomalies from long-term monthly averages during years when Columbia, Sierra, and Colorado discharges were high (left) or low (right). Precipitation is from monthly climate division data. Criteria for high and low discharge are as in Figure 7. Water years (WY) –1, 0, and +1 designate the water years prior to, during, and following the year of high or low discharge (water year is October through September). Positive/negative anomalies are plotted above/below the zero line shaded dark/light gray. Months in which the composite anomaly was significantly different from zero at the 95% confidence level using a *t*-test are designated by diamonds. Note that the vertical scale (precipitation anomaly) is less for the Colorado than it is for the Columbia and Sierra.

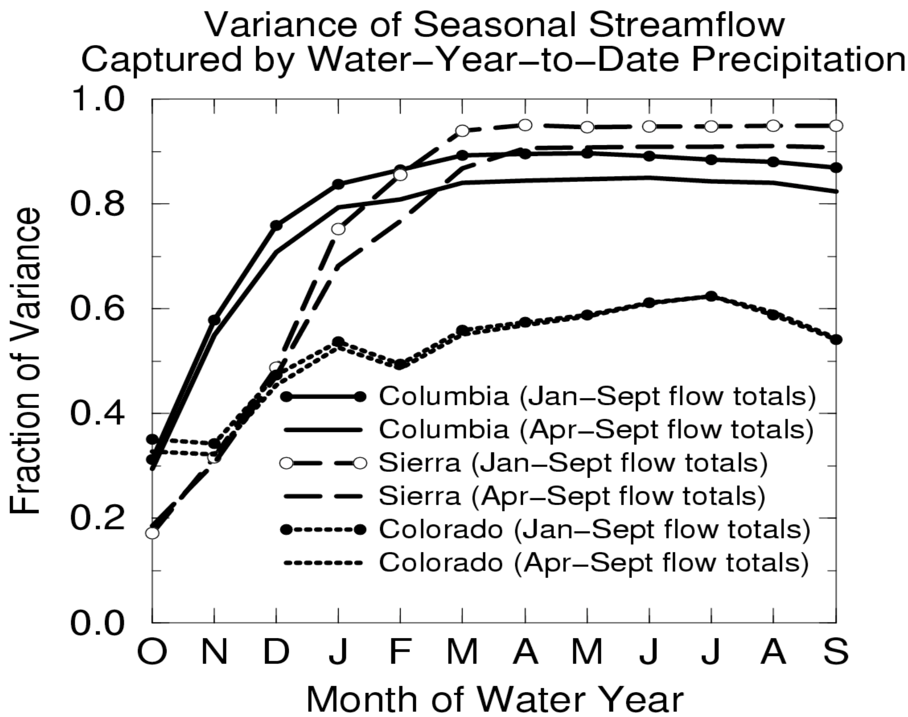


Figure 10. Variance of January–September and April–September discharges explained by accumulated precipitation anomalies beginning in October of the water year (see Figure 9) for the Columbia, Sierra, and Colorado watersheds. Precipitation is from United States monthly climate division averages, aggregated over each of the three watersheds.

Table 5. El Niño (*E*), Neutral (*N*) and La Niña (*L*) years with high/moderate/low (h/m/l) annual discharge totals, 1906-1999.

	Columbia				Sierra				Colorado		
	h	*m*	*l*		*h*	*m*	*l*		*h*	*m*	*l*
E	4	10	15	**E**	12	7	10	**E**	11	8	10
N	14	17	14	*N*	13	14	18	*N*	14	15	16
L	13	5	2	*L*	6	11	3	*L*	6	9	5

Table 6. PDO warm (*w*) and PDO cool (*c*) years with high/moderate/low *(h/m/l)* annual discharge totals, 1906-1999.

	Columbia				Sierra				Colorado		
	h	*m*	*l*		*h*	*m*	*l*		*h*	*m*	*l*
w	9	13	22	**w**	15	12	17	**w**	15	14	15
c	22	19	9	*c*	16	20	14	*c*	16	18	16

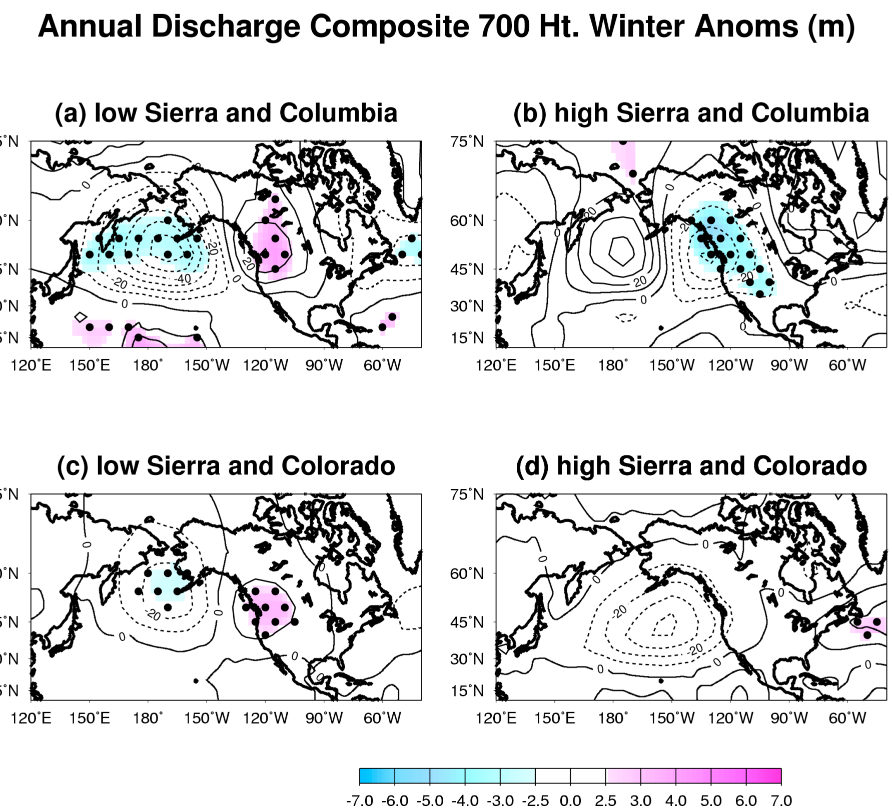


Figure 11. Average winter (December-January-February) 700 mb height anomalies during years when the Sierra and Columbia watersheds both had high (*a*) or low (*b*) annual discharges, and the Sierra and Colorado both had high (*c*) or low (*d*) annual discharges. Criteria for high and low discharges are as in Figure 4. Contours of positive/negative anomalies are solid/dashed. Grid cells at which average 700 mb height anomalies are significantly different from zero at 95% levels, using a *t*-test, are marked with heavy dots. *t*-values of positive/negative regions are shaded dark/light gray as in the key.

6. CONCLUSIONS

Climate variability and associated hydrologic variability have substantial impacts on California's hydropower and water supplies. It seems likely that these become even more important as the state's population and its needs for resources continue to grow. Climate variations both within and beyond the state boundaries have substantial influences on California resources. In order to characterize some of the transboundary hydroclimatic influences in California's water/hydropower setting, water-year river discharge totals from the west slope of the Sierra Nevada were compared to concurrent flows of the Columbia River (in the Pacific Northwest) and the Colorado River (in the southwestern United States).

Dry conditions in the three rivers have historically tended to cluster more in time than would be expected by chance. Dry conditions and wet conditions also tend to be more spatially extensive (among the three watersheds) than expected by chance. For example, years that are anomalously dry in two or more of the watersheds, or anomalously wet in two or more, occur with greater frequency than expected by chance. Dry/dry occurrences that pair the Sierra/Columbia watersheds or that pair the Sierra/Colorado watersheds are common. Co-occurrences of low flows or high flows in all three watersheds do not happen very often, but nonetheless are more frequent than expected by chance. Simultaneous low flows in all three basins occurred six times between 1906 and 1999, and, although it was not included in the present analysis, another of these massive regional dry events occurred in 2001. There is a modest tendency for opposing extremes to sometimes occur for the Columbia and Colorado Rivers, perhaps in response to PDO or ENSO episodes. Opposing extremes rarely occur for the Sierra and the Columbia or the Sierra and the Colorado watersheds.

Precipitation during winter, November through March, is critical in determining the status of the Columbia, Sierra, and (not as strongly) the Colorado water-year flow totals. Besides providing the regional water supply, the streamflows that are generated from this winter supply are strongly linked to the amount of hydroelectric power that each region produces and how much it is able to export or is compelled to import. In most years, the water year's supply is established by the end of February, owing to the dominance of winter storms in the annual precipitation cycle along the West Coast. The key factor that causes co-occurring discharge excesses and deficits in these watersheds is the broad scale of the winter atmospheric circulations, which form persistent patterns that activate or divert storms from the western states. ENSO and PDO have strong and consistent effects on the Columbia flows, but do not reliably produce high or low flows in the Sierra or Colorado Rivers. This is not to say that an organized form of the atmospheric circulation is not involved. Rather, each basin contains its own blend of circulation patterns that favor or disfavor ample yearly river flows for the region. Since most of these patterns have footprints that extend upstream over the North Pacific, it is important for progress in understanding and predicting these Pacific climate patterns to continue.

In addition to year-to-year and decade-to-decade variations in these systems, there are important seasonal regularities, which are driven at least partly by climate. These exist in the water and electric power generation and consumption systems in the western region. All three watersheds, were they unperturbed by humans, would have peak natural flows in spring to early summer, but all have been managed so that these spring–summer peaks have been substantially diminished. In California, releases from reservoirs are greatest in summer to satisfy irrigation needs and power demands then. California and the Southwest experience greatest peak demand for electric power during summer, presumably driven by air conditioning loads. In the Columbia, reservoir releases are greatest in winter to generate power because the Northwest region has greatest peak power demands then, probably to meet loads from heating and indoor appliances. These seasonally occurring regional contrasts are another complication that adds to or possibly mitigates impacts of unusual wet or dry (or cool or warm) climate spells that may persist for months to decades. The combined impacts of these regular and irregular climate influences will need to be incorporated into a truly comprehensive analysis of energy trading across the western region.

The present study has mostly examined the structure of excess or deficit annual aggregate discharge within and between these western watersheds. Not considered here is the potential added stress that may be imposed on water systems due to future climate changes. In addition to possible changes in precipitation, it is likely that the mountainous portions of these watersheds will experience major changes due to shifts in their snowmelt runoff timing due to climatic warming (Roos, 1991; Knowles and Cayan 2002).

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