Catchment Dynamics and River Processes: Mediterranean and Other Climate Regions
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Chapter 11

Hydrological effects of dams and water diversions on rivers of Mediterranean-climate regions: examples from California

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Abstract

Rivers in Mediterranean-climate and other semi-arid regions tend to be more heavily impounded and thus their hydrology more strongly affected than rivers in humid climates because demand for water is greater (to supply irrigated agriculture) and runoff is out-of-phase with demand. The impounded runoff index (ratio of reservoir capacity divided by mean annual runoff) is 0.8 on the Sacramento and 1.2 on the San Joaquin Rivers of California, much higher than rates: encountered in humid Atlantic climate regions. As a result of these high levels of impoundment, the overall magnitude and seasonal distribution of flows has changed substantially. Flood peaks tend to be reduced: the Q_2 *declined on average 53 and 81% in the Sacramento and San Joaquin River basins, respectively. On many rivers, summer baseflows have increased to supply irrigation diversions downstream, creating a flatter hydrograph that no longer supports dynamic channel processes and the aquatic ecosystem that depends upon such channel dynamics. Vegetation has encroached in the formerly active channels of many rivers in response to reduced flood scour and sediment supply.*

Keywords: impounded runoff, river regime, reservoirs, Mediterranean basins

1. Introduction

Flow variability is an important characteristic of river systems, with implications for river geomorphology, ecology, and human uses (Puckridge et al., 1998). Many aquatic and riparian-dwelling organisms are adapted to the seasonal and inter-annual variations in flow that characterize their native river habitats, including periodic high flows (Junk et al., 1989; Poff et al., 1997). Flow variability tends to be greater in arid- than humid-climate regions (McMahon, 1979; Finlayson and McMahon, 1988), with implications that

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infrequent, episodic events exert a greater influence on river form and ecology (Wolman and Gerson, 1978; Hecht, 1994), and reservoir storage is proportionally greater (Thoms and Sheldon, 2000). Mediterranean-climate rivers are similar to arid-climate rivers in their high variability in flow and sediment load, but have higher rainfall and a pronounced seasonality that is predictable, at least in their overall characteristics, with cool, wet winters, and warm, dry summers (Conacher and Sala, 1998; Gasith and Resh, 1999). Seasonal precipitation and flow variability are high, with rainfall concentrated in winter months. Inter-annual flow variability is likewise high, driven by high variability in precipitation. The variability in annual precipitation can be illustrated by comparing the range in annual precipitation values for selected stations with similar mean annual rainfall in Mediterranean-climate vs. humid Atlantic climate regions of North America. Cavendish, Vermont, with a mean precipitation of 1120 mm y^{-1}, has a much smaller range of annual values than Healdsburg, California, with 1097 mm y^{-1}, and a coefficient of variation (CV) of only 0.14 contrasted with a CV of 0.33 for Healdsburg (Table 11.1).

The seasonal pattern of precipitation in Mediterranean-climate regions means that water availability and demand are out-of-phase. Precipitation and runoff occur (almost exclusively) in winter, while plants are dormant and demand for irrigation (and hydroelectric generation for air conditioning) is lowest. Thus, seasonal and inter-annual water storage is needed to meet the basic needs of human populations, to support industrial-scale agriculture, and in some cases for flood control. As a result, Mediterranean-climate rivers tend to be more highly regulated than humid climate rivers of comparable size. For example, Spain (whose climate is Mediterranean except in the northwestern provinces) has 1200 large dams (more than any other country in Europe and 2.5% of the population of dams of the world), which collectively impound 40% of the country's average annual runoff (http://www.dams.org). This is a much higher rate of impoundment that typically encountered in more humid regions. For example, if we consider similarly sized German rivers, reservoir capacity is from 5 to 18% of the annual

Table 11.1. Precipitation variation for illustrative Mediterranean and Atlantic climate stations.

Location	Elevation (meters a.s.l.)	Climate type	Annual mean (mm)	Annual minimum (mm)	Annual maximum (mm)	Standard deviation	Coefficient of Variation
Big Sur, CA	61	Mediterranean	1000	460	2260	1560	0.36
Healdsburg, CA	33	Mediterranean	1100	350	2440	1410	0.34
Springfield, MO	384	Humid	1070	640	1610	889	0.21
Cavendish, VT	242	Atlantic	1120	770	1430	625	0.14
Kingston, RI	33	Atlantic	1260	780	1780	830	0.17

Source: National Climatic Data Center database, http://www.ncdc.noaa.gov/oa/ncdc.html runoff on the Elbe, Rhine, and Wesser Rivers (P. Ergenzinger and C. de Jong, Free University of Berlin, personal communication, December 2001), and the reservoir capacity in relation to annual runoff on the Potomac River (draining the Appalachian Mountains of eastern North America) is less than 20%.

As reviewed by Puckridge et al. (1998), flow variability in rivers has been characterized by a range of statistics, including slopes of flood frequency curves, seasonal distribution of mean monthly flows, coefficients of variation of annual maxima and minima, differences between mean and median flows, and other measures of skewness. Effects of reservoirs on flow regime have been documented in many studies, using a variety of statistical techniques (e.g. Petts, 1984; Williams and Wolman, 1984; Richter et al., 1996; Thoms and Sheldon, 2000). This chapter presents an analysis of hydrologic effects of dams and diversions on the Sacramento–San Joaquin River system of Mediterranean-climate. California, in which we test the degree to which the relative degree of impoundment can explain the degree of change in flow. These hydrologic changes have geomorphic and ecological consequences, which we discuss briefly, but whose development is beyond the scope of this chapter.

2. Area description

Coastal California experiences a Mediterranean-climate, and rivers draining the Sierra Nevada range have a combined Mediterranean-montane runoff regime, influenced by snowmelt runoff. Eastern portions of the state, in the rain shadow of large mountain ranges, experience a semi-arid climate, but precipitation does not follow the classic Mediterranean seasonal pattern of winter rains and dry summers. The state's largest river system, the Sacramento–San Joaquin, drains over 160,000 km^2 (more than 40% of the state's land area). The Sacramento River flows south–southeastward along the axis of the Great Central Valley, meeting the north–northwestward-flowing San Joaquin at their inland delta, and thence the combined rivers flow westward through Suisun, San Pablo, and San Francisco Bays to debouch into the Pacific Ocean at the Golden Gate. Most of the runoff is from the Sierra Nevada mountain range, a north–northwest trending tilted fault block with elevations exceeding 4 km, which receives substantial precipitation thanks to orographic lifting of moist Pacific air in winter storms. Much of this precipitation falls as snow in high elevations, and the snowmelt runoff from the Sierra constitutes the principal developed water source in California. The major tributaries to the Sacramento and San Joaquin Rivers have been impounded by since the late 19th and early 20th century, to divert water for gold mining in the foothills mining districts and for agriculture on the valley floor (California State Lands Commission, 1993). Through the 20th century new reservoirs have been constructed and small ones replaced with larger ones, such that by the end of the century there were over 1400 dams in the state large enough to fall under the regulatory purview of the Division of Safety of Dams (dams more than 4.6 m high and/or impounding more than 61,700 m^3) (California Department of Water Resources, 1988). The Sacramento–San Joaquin River system, source of much of the irrigation and municipal water for the state, is heavily plumbed.

3. Methods

We compiled hydrologic data on 14 major rivers in Sacramento–San Joaquin River system and computed changes in flow regime due to reservoir regulation and diversion. Our principal data source was the US Geological Survey published flow data, available online at http://water.usgs.gov. Data included mean daily flows, mean monthly flows, annual runoff, and annual peak flows. As a rough indicator of the degree to which reservoirs can alter flow regime downstream, we calculated the Impounded Runoff index, IR (expressed as a decimal or percentage) for major tributaries to the Sacramento River, as per Batalla et al. (2004),

$$\mathrm{IR} = \text{reservoir capacity}/\text{mean annual inflow}$$

We obtained reservoir capacities from California Department of Water Resources (1988) and mean annual runoff from suitably located stream gauges, using pre-dam runoff values for the IR calculation. The ratio of storage capacity to mean annual flow has been used previously, for example, by Brune (1953) as the independent variable from which to predict reservoir trap efficiency. IR can be viewed in terms of average residence time, although the high inter-annual variability in flow means that it will never be a true residence time. For example, an IR of 1.0 implies an average residence time of 1 year, but because at least half of the years have flow less than this amount and some years greatly exceed the average, actual residence times should be less. In our calculations, we used simply the stated total reservoir capacity, as this was available for all reservoirs. This analysis could potentially be improved in the future by distinguishing between active storage (the volume of water that can actually be released from the reservoir) and dead storage (the volume of water that lies below the elevation of the reservoir outlet), as we would expect the former to be a better indicator of the potential for hydrologic modification.

For pre-dam mean annual runoff, we sought a flow value that would best represent flow prior to human alteration. In some cases, suitable gauging records existed pre- and post-reservoir construction. In these cases, we calculated our mean annual runoff value from the pre-dam data. In other cases, we relied on "unimpaired flow" data calculated by the dam operator. In rivers with significant diversions above the gauge (e.g. Tuolumne and San Joaquin below Friant Dam) we added in canal flows where necessary to obtain a mean annual runoff that would more closely reflect pre-dam conditions. The hydrologic effect of a reservoir can be expected to attenuate downstream, so we used post-dam records for gauges just downstream of the large storage reservoirs in the foothills, except for the Yuba River, where the downstream reservoir is exceeded in capacity by an upstream reservoir. To illustrate seasonal changes in flow on river reaches below reservoirs, we plotted mean monthly flows from pre- and post-dam periods. We calculated the pre-dam–post-dam correlation coefficient for each gauge series ($\Phi_{\mathrm{pre,post}}$) by dividing the covariance of the two data sets by the product of their standard deviations:

$$\Phi_{\mathrm{pre,post}} = \mathrm{cov}_{\mathrm{pre,post}}/(\sigma_x \cdots \sigma_y)$$

where $1 \geq \Phi \geq -1$, $\mathrm{cov}_{\mathrm{pre,post}} = 1/n[\sum(\mathrm{pre}_i - \mu_x)(\mathrm{post}_i - \mu_y)]$, σ is the standard deviation, n the number of data, and μ the mean value of the distribution. Values near 1 indicate that the post-dam flow regime closely matches the pre-dam regime in timing, and thus the seasonal pattern of flow has not changed. However, changes in the magnitude of flows would not be detected by this variable if the seasonal distribution was similar to pre-dam. Values of $\Phi_{\mathrm{pre,post}}$ near 0 indicate that the post-dam monthly regime is independent of the natural pre-dam pattern, and values near -1 reflecting inversion of the flow regime.

We conducted flood frequency analyses (annual maxima series) (Dunne and Leopold, 1978) for the 14 rivers. We focused on relatively frequent floods (i.e. Q_2, Q_{10}). Flows with a return period of about 2 years are reported in the geomorphic literature to be the channel-forming discharges for many rivers, but in semi-arid climates channel form tends to be influenced by longer return period discharges. (Wolman and Gerson 1978). Interpretation of the Q_2 and Q_{10} flows is straightforward and empirical, since no extrapolation outside the actual range of data is necessary. To explore the relation between degree of impoundment (IR) and degree of hydrologic changes, we plotted the changes in flood magnitudes against IR.

4. Results and analysis

4.1. Degree of regulation

Rivers in the Sacramento–San Joaquin basin are highly impounded. The largest reservoirs are Shasta on the Sacramento (capacity 5.62 $m^3 \times 10^9$), Oroville on the Feather (capacity 4.36 $m^3 \times 10^9$), and New Melones on the Stanislaus (capacity 2.99 $m^3 \times 10^9$). Overall basin-wide IRs are 0.80 for the Sacramento and 1.2 for the San Joaquin, with individual river IRs ranging from 0.53 (Stony Creek) to 4.63 (Putah Creek) (Table 11.2, Fig. 11.1). Although reservoirs are found at nearly every elevation, storage is concentrated in large reservoirs located in the foothills. For example, there are 28 impoundments in the Stanislaus River basin, but the large foothills reservoir, New Melones, accounts for 85% of the storage. On the Stanislaus, Tuolumne, and Merced Rivers, larger reservoirs in the 1960s and 1970s (Table 11.2) replaced reservoirs built in the 1920s (with under 0.3 $m^3 \times 10^9$ capacity).

Roughly half of these dams were built and are operated by federal agencies such as the US Army Corps of Engineers (Black Butte, Camp Far West, New Hogan) or the US Bureau of Reclamation (Shasta, Whiskeytown, Folsom, New Melones, and Friant) or the California Department of Water Resources (Oroville), with the rest owned by local irrigation districts or power utilities (Monticello, New Bullards Bar, Pardee, Camanche, New Don Pedro, and New Exchequer). The many smaller upstream dams also tend to be owned by local irrigation districts or utilities.

The purposes of these reservoirs vary and are usually multiple, but most of the storage is devoted to irrigation. Many dams are jointly operated, with the US Army Corps of Engineers responsible for operating the flood pool (the storage devoted to flood control during the winter months) and another agency managing the rest of the storage capacity.

4.2. Changes in mean monthly flow

Mean monthly flows show a range of changes post-dam, from essentially no change on the Bear River below Camp Far West Reservoir, to the flattening of the annual hydrograph

Table 11.2. Reservoirs and impoundment ratios for major rivers, Sacramento–San Joaquin River system (California).

River	Dam	Year	Drainage Area (km^2)	USGS Gauge		Avg. Annual Runoff[a] (m^3 × 10^9)	Large“foothills” Reservoir Capacity[b]		Total reservoir Storage Capacity[c]	
				Name	Avg. over:		m^3 × 10^9	IR	m^3 × 10^9	IR
Sacramento	Shasta	1945	17262	at Keswick	1946–1962	7.278	5.617	0.77	5.384	0.74
West-side tributaries										
Clear Creek	Whiskeytown	1963	521	Near Igo	1941–1962	0.369	0.297	0.81	0.327	0.89
Stony Creek	Black Butte	1963	1919	Below Black Butte Dam Near Orland	1956–1990	0.568[4]	0.197	0.35	0.303	0.53
Putah Creek	Monticello	1957	1492	Near Winters	1931–1956	0.427	1.976	4.63	1.976	4.63
East-side tributaries										
Feather	Oroville	1968	9342	at Oroville	1902–1967	5.215	4.364	0.84	6.714	1.29
Yuba[e]	Englebright	1940	2870	Below Englebright	1942–1995	2.178	0.087	0.04	1.739	0.80
	New Bullards Bar	1970					1.199	0.55		
							1.284	0.59		
Bear	Camp Far West	1963	738	Near Wheatland	1930–1963	0.380	0.126	0.33	0.289	0.76
American	Folsom	1956	4890	at Fair Oaks	1905–1954	0.354	1.246	0.37	2.261	0.67
Mokelumne	Pardee	1929	1489	Below Camanche Dam	1931–1963	0.744	0.259	0.35	1.032	1.39
	Camanche	1963	1603				0.531	0.71		
							0.790	1.06		

Calaveras	New Hogan	1963	940	Below New Hogan Dam, Near Valley Springs	1961–1990	0.205	0.400	1.96	0.396	1.93
Stanislaus	Melones	1926	2331	Below Goodwin Dam	1957–1978	0.202[f]	0.145	0.12		
	New Melones	1979	2331	Near Knight's Ferry			2.986	2.48	3.518	2.93
Tuolumne	Don Pedro	1923	3994	Below La Grange Dam,	1971–1995	1.772[g]	0.309	0.17		
	New Don Pedro	1971	3994	Near La Grange			2.505	1.41	3.444	1.94
Merced	Exchequer	1926	2694	Below Merced Falls,	1901–1925	1.290	0.347	0.27		
	New Exchequer	1967	2694	Near Snelling			1.273	0.99	1.305	1.01
San Joaquin	Friant[h]	1941	4242	Below Friant	1908–1940	2.095	0.643	0.31	1.140	0.54

[a] Pre-dam data unless otherwise indicated; averages as reported in USGS 1995.

[b] Reservoir capacities from DWR (1988).

[c] Total reservoir capacity includes only those reservoirs with storage capacity greater than 0.648 $m^3 \times 10^6$.

[d] Average. annual runoff as measured for full period as published in USGS 1990, adjusted for diversions.

[e] On the Yuba River, the largest reservoir is not the most downstream. Englebright Dam (1940) has a drainage area of 2870 km^2 but a reservoir capacity of only 0.057 $m^3 \times 10^9$, much smaller than New Bullards Bar, which is located on the North Fork and has a capacity of 0.785 $m^3 \times 10^9$. Average value reported for entire POR only (i.e. 1942–1995) in USGS (1995).

[f] Average annual runoff for pre-dam period of record at Knight's ferry of 0.426 $m^3 \times 10^9$ (1957–1978), plus average diversion to South San Joaquin Canal of 0.261 $m^3 \times 10^9$ (1914–1995) and average diversion to Oakdale Canal of 0.102 $m^3 \times 10^9$ (1914–1995), as published by USGS (1995).

[g] Average annual runoff for post dam period below La Grange Dam of 0.528 $m^3 \times 10^9$ (1971–1995) because comparable pre-dam values were not reported in USGS 1995; plus average diversion to Modesto Canal of 0.250 $m^3 \times 10^9$ (1909–1995), and average diversion to Turlock Canal of 0.385 $m^3 \times 10^9$.

[h] Millerton Reservoir drainage area and capacity from USGS (1995).

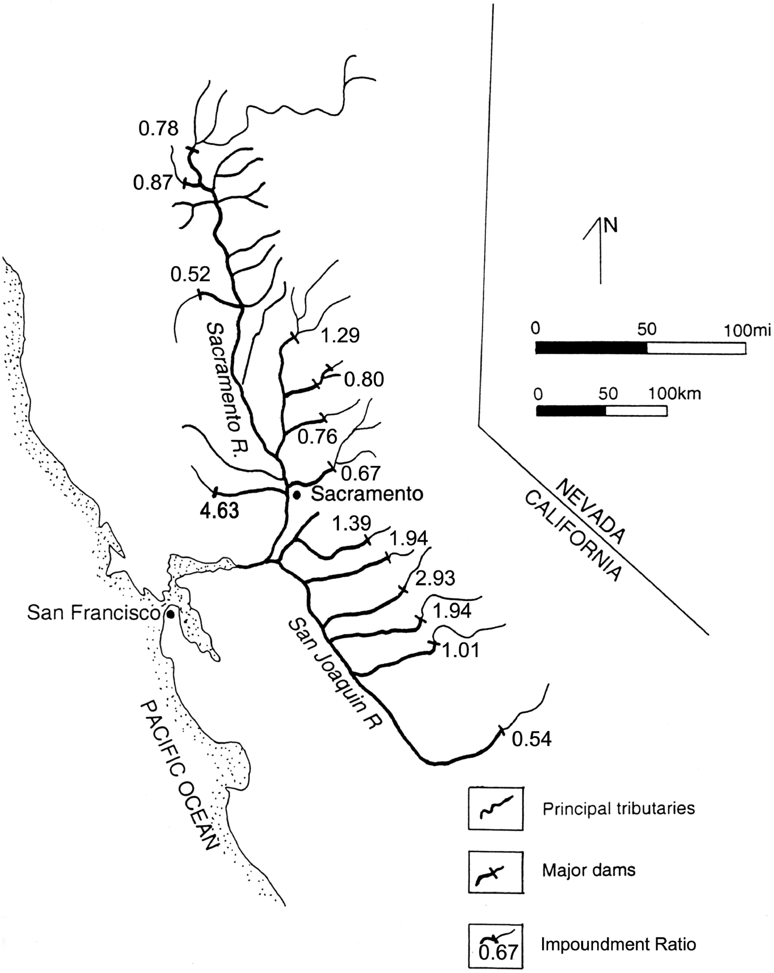

Figure 11.1. Map of principal tributaries of the Sacramento and San Joaquin Rivers, showing locations of major foothills dams and total impoundment ratio (IR). See Table 11.2 for list of rivers.

through eliminating winter peaks and increasing summer base flows by an order of magnitude on Putah Creek (Fig. 11.2). The value of IR is a good though imperfect predictor of change, yielding a regression relation ($r^2 = 0.53$, $N = 12$, $p < 0.05$) (Table 11.3, Fig. 11.3). Only 12 points are used in the regression because these are the only ones with adequate pre-dam mean monthly data (Table 11.3). Only 11 of the 12 points are visible in Figure 11.3 because the Sacramento and Yuba rivers plot directly on one

Figure 11.2. Pre- and post-dam mean monthly flows for 12 major rivers in the Sacramento–San Joaquin River system. The same rivers are listed in Tables 11.2 and 11.3, except for Stony Creek and Calaveras River, which are not shown because their pre-dam data series were very short.

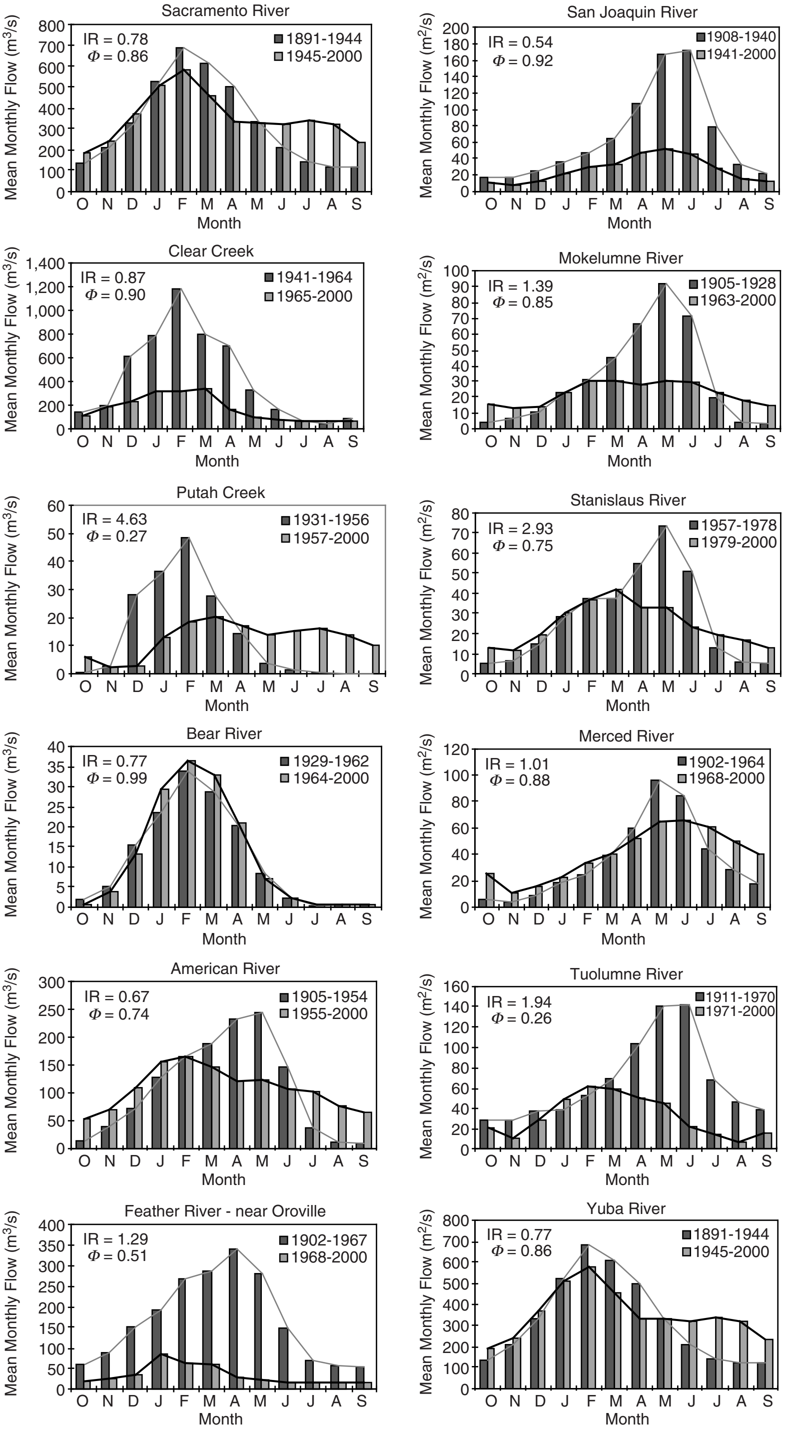
Sacramento River
IR = 0.78
Φ = 0.86
1891-1944
1945-2000
Mean Monthly Flow (m3/s)
0 100 200 300 400 500 600 700 800
O N D J F M A M J J A S
Month
San Joaquin River
IR = 0.54
Φ = 0.92
1908-1940
1941-2000
Mean Monthly Flow (m2/s)
0 20 40 60 80 100 120 140 160 180 200
Clear Creek
IR = 0.87
Φ = 0.90
1941-1964
1965-2000
0 200 400 600 800 1,000 1,200 1,400
Mokelumne River
IR = 1.39
Φ = 0.85
1905-1928
1963-2000
0 10 20 30 40 50 60 70 80 90 100
Putah Creek
IR = 4.63
Φ = 0.27
1931-1956
1957-2000
0 10 20 30 40 50 60
Stanislaus River
IR = 2.93
Φ = 0.75
1957-1978
1979-2000
0 10 20 30 40 50 60 70 80
Bear River
IR = 0.77
Φ = 0.99
1929-1962
1964-2000
0 5 10 15 20 25 30 35 40
Merced River
IR = 1.01
Φ = 0.88
1902-1964
1968-2000
0 20 40 60 80 100 120
American River
IR = 0.67
Φ = 0.74
1905-1954
1955-2000
0 50 100 150 200 250 300
Tuolumne River
IR = 1.94
Φ = 0.26
1911-1970
1971-2000
0 20 40 60 80 100 120 140 160
Feather River - near Oroville
IR = 1.29
Φ = 0.51
1902-1967
1968-2000
0 50 100 150 200 250 300 350 400
Yuba River
IR = 0.77
Φ = 0.86
1891-1944
1945-2000
0 100 200 300 400 500 600 700 800

Table 11.3. Changes in mean monthly flow pattern and peak flows for selected rivers in the Sacramento–San Joaquin River system (California).

River	IR (total)	$\Phi_{\text{pre,post}}$	Q_2 (m^3/s)			Q_{10} (m^3/s)		
			Pre	Post	% change	Pre	Post	% change
Clear Creek	0.87	0.90	203.9	107.6	−47	467.3	269.0	−42
Stony Creek[a]	0.52	[b]	566.4	192.6	−66	1925.8	495.6	−74
Putah Creek	4.63	0.27	719.9	44.2	−94	2224.0	216.7	−90
Sacramento	0.78	0.86	3109.5	2095.7	−33	5833.9	3568.3	−39
Feather (near Oroville)	1.29	0.51	1965.4	1243.8	−37	6010.4	4387.6	−27
Yuba	0.77	0.86	962.9	495.6	−49	3398.4	2265.6	−33
Bear	0.76	0.99	278.8	175.6	−37	675.5	793.0	17
American	0.67	0.74	1116.7	463.5	−58	3065.6	2226.8	−27
Mokelumne	1.39	0.85	263.4	53.8	−80	594.7	147.3	−75
Calaveras	1.94	[b]	354.0	55.2	−84	807.0	229.0	−72
Stanislaus	2.93	0.75	266.2	87.8	−67	991.2	186.9	−81
Tuolumne	1.94	0.26	589.1	99.1	−83	1324.0	239.3	−82
Merced	1.01	0.88	382.3	59.5	−84	934.6	201.1	−78
San Joaquin	0.54	0.92	396.1	49.0	−88	1041.0	386.4	−63

[a] Pre-dam flood frequency estimated from USACE (1987) (Stony Creek) and USACE, 1983 (Calaveras River).

[b] Not available due to limited pre-dam gauging record.

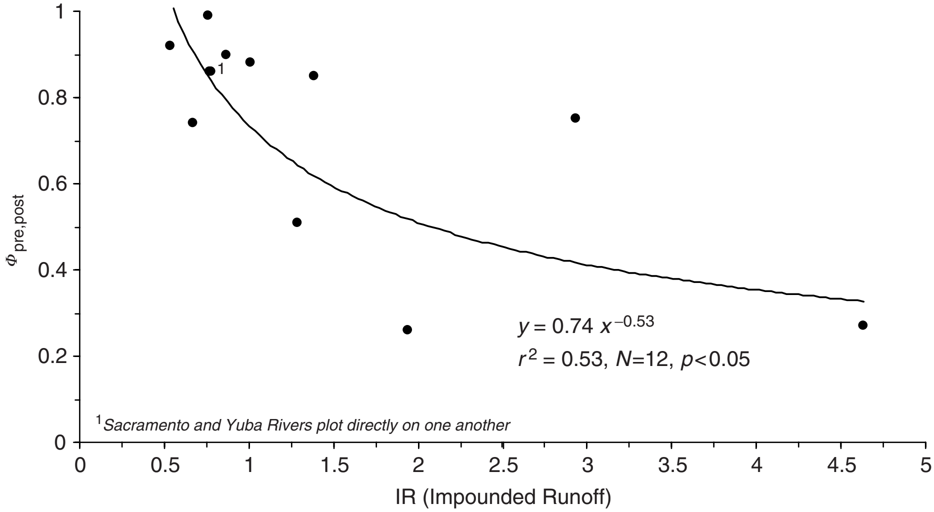

Figure 11.3. Changes in monthly flow regime (expressed as the correlation coefficient $\Phi_{\text{pre,post}}$) as a function of the degree of impoundment (IR) for 12 major rivers in the Sacramento–San Joaquin River system (the data set of 14 rivers less Stony Creek and Calaveras Rivers, for which inadequate pre-project data exist to characterize pre-dam mean monthly flows).

another. The tributaries with the greatest change in seasonality are the Tuolumne River and Putah Creek, which have Φ values of 0.26 and 0.27, respectively, and IRs of 1.94 and 4.63, respectively. On the Tuolumne, the seasonal change is the result of diversion of snowmelt runoff and elimination of the spring-early summer high flows, with a net reduction in total flow. On Putah Creek, diversions occur downstream of the gauge, so the seasonal change results from elimination of winter runoff peaks and sustained, augmented releases in the summer.

Inspection of the mean monthly flow plots shows reduction in seasonal high flows for both winter-rainfall-runoff-dominated rivers (e.g. Sacramento, Clear, Putah, Bear, and Yuba) and spring-snowmelt-runoff-dominated rivers (e.g. San Joaquin, Mokelumne, Stanislaus, Merced, Tuolumne, American, and Feather). In some rivers, the flood waters stored by the reservoir are released during the summer for diversion by irrigators downstream, so the gauge records may reflect simply a seasonal redistribution of flow, with no net reduction in annual flow (e.g. Putah). In other cases, irrigation diversions are made upstream of the gauge, so the annual flow is reduced as well. Friant Dam on the San Joaquin River is the most compelling example of this, with two canals (with capacity of about 150 $m^3 s^{-1}$) diverting directly from the dam. Values of Φ ranged from 0.26 to 0.99, with a median value of 0.85.

4.3. Changes in flood frequency

Flood frequency plots show progressive reduction in annual peak flows with expansion of reservoir capacity, as illustrated by the Mokelumne River below Camanche Dam, where downward shifts in the curve resulted from construction first of Pardee Reservoir in 1929, then the larger Camanche Reservoir downstream in 1963 (Fig. 11.4). Q_2 decreased from a pre-dam value of 260 $m^3 s^{-1}$ to just over 50 $m^3 s^{-1}$ after completion of Camanche.

Overall, Q_2 declined from 33 to 94% in these tributaries, with an average reduction of 65%. In general, the southern Sierran tributaries of the San Joaquin River experienced greater reduction in Q_2 than the northern Sacramento River tributaries, a pattern attributable in part to the greater reservoir storage in the San Joaquin. Q_{10} showed a similar pattern, with reductions ranging from 17 to 90%, and an average reduction of 57%. Although specific reservoir purpose and consequent operations rules varied among reservoirs, and thus the expected alteration in flood regimes, we hypothesized that the simple IR variable could provide some prediction of the degree of reduction in flood magnitudes. Plots of reduction in post-dam Q_2 and Q_{10} against IR show a trend toward greater reduction with higher IR, but the scatter is high (Fig. 11.5).

5. Discussion and conclusions

Flow variability has been a main motivation for, and casualty of, reservoir construction in Mediterranean-climate regions. The degree of hydrologic modification in these regions has not been widely documented or the implications fully appreciated. The highly seasonal pattern of discharge, so characteristic of Mediterranean-climate rivers and so inconvenient for human uses of rivers, has been reduced or even reversed in some cases,

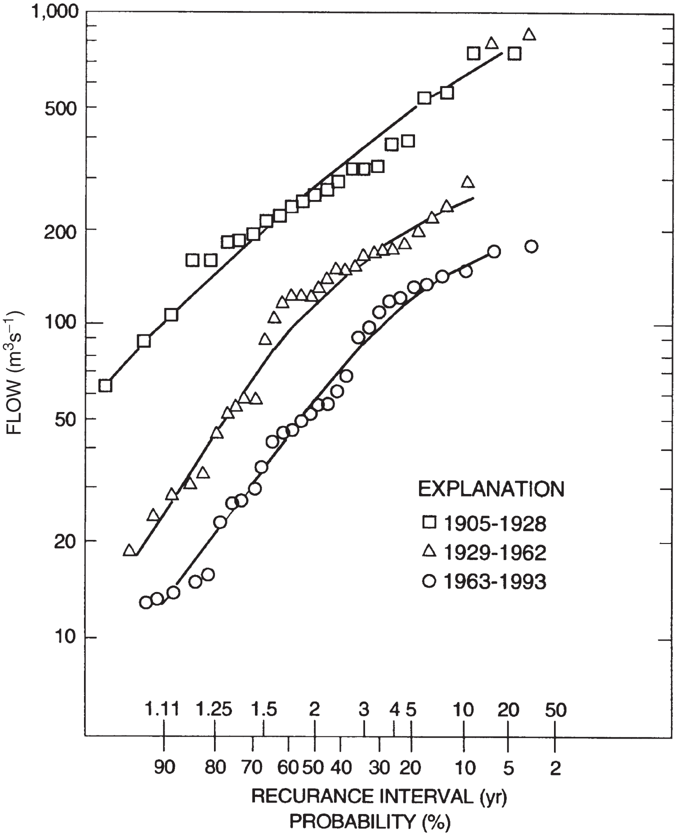

Figure 11.4. Flood frequency curves for the Mokelumne River below Camanche Dam for three time periods: before Pardee Dam (1905–1928), after Pardee Dam but before Camanche Dam (1929–1962), and after Camanche Dam (1963–1993) (Adapted from the Federal Energy Regulatory Commission, 1993).

resulting in a pronounced flattening of the annual hydrograph. The potential for such changes is greater on rivers with higher storage relative to annual runoff (IR), though the operating rules of specific reservoirs vary enough that IR is not sufficient to predict the degree of hydrologic modification.

For 22 regulated reaches in the Ebro River basin of Spain, Batalla et al. (2004) documented decreases in magnitude of Q_2 and Q_{10} floods averaging over 30%, compared with decreases of over 60% we document here for Q_2 and Q_{10} in the Sacramento–San Joaquin River system. In a general way, this can be attributed to greater reservoir storage in the Sacramento and San Joaquin River basins than in the Ebro River Basin (IR values of 0.8 and 1.2 vs. 0.6, respectively), but the relations between IR and flood reduction in individual rivers are variable. Post/pre-dam Q_2 and Q_{10} ratios plotted against IR yielded r^2 values of 0.52 and 0.60, respectively for the Ebro basin (Batalla et al., 2004), contrasted with r^2 values of 0.32 and 0.42 obtained here for the Sacramento–San Joaquin River system (Fig. 11.4). (The Ebro relation was linear, while a better fit for the Sacramento was obtained with a power function. Post-dam flood magnitude decreased rapidly for values of

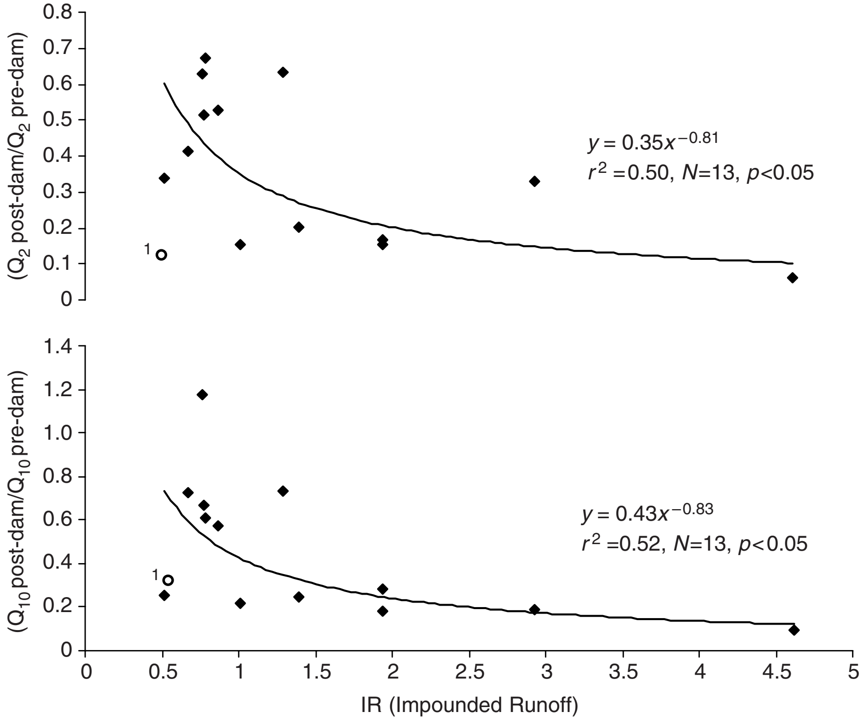

Figure 11.5. Reduction in flood magnitudes after dam construction in rivers of California, plotted against IR, for Q_2 and Q_{10}.

IR up to 1, more slowly for greater IR values, as the floods have already been substantially reduced.

The reduction in seasonality of runoff, accompanied by reduction in peak flows, has utterly changed the nature of many Mediterranean-climate rivers, for instance in Spain (Batalla et al., 2004) and California, as shown in this chapter. The reductions in flow magnitude result in reduced stream power available for sediment transport, which combined with the trapping of coarse sediment by the reservoirs, results in reduced sediment transport in reach downstream of these dams. As noted by Inbar (1992), Mediterranean-climate regions are mainly in active tectonic areas, characterized by steep relief, a factor that would favor high sediment yields (Milliman and Syvitski, 1992). Thin vegetative cover, typical of these regions, would also favor high sediment yields (Langbein and Schumm, 1958). Thus, Mediterranean-climate regions tend to have relatively high sediment yields, though by no means the highest in the world, as factors such as basin relief, uplift rates, and lithology tend to be dominant determinants of sediment yield (Milliman and Syvitski, 1992). The extreme reductions in sediment supply and transport capacity below reservoirs in Mediterranean climate regions thus means that the relative change wrought by dams should be greater in Mediterranean-climate rivers than most humid-climate rivers.

In Mediterranean-climate regions, the high variability in runoff means that large, infrequent floods tend to carry a greater percentage of runoff than would be the case in a comparably sized humid climate river, and since sediment transport is a power function of discharge, these floods carry proportionately higher sediment loads. As a result, channel processes in Mediterranean (and other semi-arid regions) tend to be more episodic (Wolman and Gerson, 1978; Hecht, 1994) than in comparable humid-climate and snowmelt rivers, where flows are more stable and small floods (e.g. $Q_{1.5}$) largely control channel processes and form (Leopold et al., 1964). Accordingly, reservoir-induced shifts from episodic to stable flow regime represent a profound transformation in riverine process for Mediterranean-climate rivers. In consequence, impounded rivers in California have experienced encroachment of vegetation into the formerly active channel and channel narrowing, as exemplified by the Trinity River (Kondolf and Wilcock, 1996).

Reservoir-induced reduction in flow variability and sediment load has ecological implications as well. Native species of Mediterranean-climate rivers and floodplains are adapted to the highly seasonal flow, sediment transport, and bed disturbance, and can survive prolonged dry periods, allowing them to colonize these habitats. However, once flow variability is reduced by regulation, exotic species that were formerly excluded by the highly variable flow regime may have a competitive advantage under the new, more stable flow regime. In California, the percentage of exotic species is greater in reaches below dams than elsewhere (Moyle, 2003).

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