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THE INFLUENCE OF MAJOR DAMS ON HYDROLOGY THROUGH THE DRAINAGE NETWORK OF THE SACRAMENTO RIVER BASIN, CALIFORNIA

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ABSTRACT

This paper reports basinwide patterns of hydrograph alteration via statistical and graphical analysis from a network of long-term streamflow gauges located various distances downstream of major dams and confluences in the Sacramento River basin in California, USA. Streamflow data from 10 gauging stations downstream of major dams were divided into hydrologic series corresponding to the periods before and after dam construction. Pre- and post-dam flows were compared with respect to hydrograph characteristics representing frequency, magnitude and shape: annual flood peak, annual flow trough, annual flood volume, time to flood peak, flood drawdown time and interarrival time. The use of such a suite of characteristics within a statistical and graphical framework allows for generalising distinct strategies of flood control operation that can be identified without any *a priori* knowledge of operations rules. Dam operation is highly dependent on the ratio of reservoir capacity to annual flood volume (impounded runoff index). Dams with high values of this index generally completely cut off flood peaks thus reducing time to peak, drawdown time and annual flood volume. Those with low values conduct early and late flow releases to extend the hydrograph, increasing time to peak, drawdown time and annual flood volume. The analyses reveal minimal flood control benefits from foothill dams in the lower Sacramento River (i.e. dissipation of the down-valley flood control signal). The lower part of the basin is instead reliant on a weir and bypass system to control lowland flooding. Data from a control gauge (i.e. with no upstream dams) suggest a background signature of global climate change expressed as shortened flood hydrograph falling limbs and lengthened flood interarrival times at low exceedence probabilities. This research has implications for flood control, water resource management, aquatic and riparian ecosystems and for rehabilitation strategies involving flow alteration and/or manipulation of sediment supplies. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: rivers/streams; watershed; runoff; hydrograph alteration; river network; dams

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INTRODUCTION

Although the influence of major dams on hydrographs has been well studied directly below dams, there is a paucity of research on the basinwide influence of multiple dams on flow within a river network. Specifically lacking is understanding of how the influence of any particular dam propagates or dissipates through the fluvial system, and how many dams operated for multiple uses complicate impacts on hydrology in downstream portions of a large basin. Such information is required to assess the efficacy of dams on flood control at any location in the fluvial system, to predict the consequences of global climate change on basin hydrology or to anticipate the network effects of dam re-operation (i.e. modification of dam outflow) to rehabilitate riverine habitats. In this paper, I investigate the impact of multiple-use dams on hydrology through the river network in the Sacramento River basin of California, where large dams play a significant role in basin hydrology and where flow data are plentiful before and after dam construction. The work is relevant to any large river basin under the influence of multiple dams managing water for various uses.

Dams influence sediment conveyance (e.g. Andrews, 1986; Topping *et al*., 2000a; Willis and Griggs, 2003), channel morphology (e.g. Gregory and Park, 1974; Williams and Wolman, 1984; Chien, 1985; Xu, 1996;

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Brandt, 2000; Topping *et al*., 2000b) and ecology (e.g. Rood and Mahoney, 1990; Ligon *et al*., 1995; Power *et al*., 1996; Richter *et al*., 1996; Wootton *et al*., 1996; Koel and Sparks, 2002). Such second and third order impacts on fluvial systems generally result from the first order influence of dams: hydrograph alteration.

Various studies have tackled hydrograph alteration by analysing flow data directly below dams (Gregory and Park, 1974; Williams and Wolman, 1984; Chien, 1985; Dynesius and Nilsson, 1994; Collier *et al*., 1996; Graf, 1999; Galat and Lipkin, 2000; Magilligan and Nislow, 2001; Magilligan *et al*., 2003; Pegg *et al*., 2003; Batalla *et al*., 2004), though relatively sparse attention has been paid to alteration of hydrograph shape and how specific dam operations affect hydrograph characteristics. In general, dams appear to decrease flow peak frequency, magnitude and duration while increasing frequency, magnitude and duration of low flows, independent of region (Magilligan and Nislow, 2001; Magilligan *et al*., 2003). Magilligan *et al*. (2003) controlled for basin scale and dam type to generalize about hydrograph alteration, but deviations from such generalizations are likely in flow records from gauging stations located various distances down valley, below river confluences and where effects of multiple upstream dams are integrated.

Although the effect of dams on flow through a network have been extensively studied in a hydraulic modelling context (e.g. Fread, 1980), few papers have analysed flow records to address the problem of how hydrograph alteration from dams varies through the river network. Richter *et al*. (1998) presented a map of the Colorado basin that illustrates the spatial distribution of averaged hydrologic alteration across six hydrologic parameters and found dissipation of alteration with distance downstream. Batalla *et al*. (2004) also determined that the influence of dams on mean monthly flow and flood magnitude diminished with distance downstream due to increasing drainage area. Similarly, Galat and Lipkin (2000) found that the effect of hydrograph alteration dissipates below tributary junctions. However, there are no studies that systematically and probabilistically analyse down-valley patterns in hydrograph alteration arising from the network effects of major upstream dams.

In this paper, I report statistical analysis of data from a set of long-term flow gauges to demonstrate how alteration of hydrograph peak, shape, timing, volume and baseline flow differs by dam, and propagates and/or dissipates through the Sacramento River basin drainage network. I present spatial maps that graphically compare pre- and post-dam hydrologic series for the entire empirical distribution of six hydrograph characteristics. I interpret the statistical and graphical data in the context of dam operation the details of which were not known *a priori*.

STUDY AREA

The Sacramento River basin drains 68 000 km^2 including the Sierra Nevada, Coast Ranges, Modoc Plateau and Trinity Mountains and is controlled by seven large dams (storage $> 1 \times 10^8$ m^3, Table I) that are operated for various combinations of hydroelectricity, water supply, flood control, irrigation and recreation. The basin is under the influence of a Mediterranean climate that is strongly affected by El Nino Southern Oscillation (ENSO) and Pacific-North America (PNA) teleconnection climatic patterns (Redmond and Koch, 1991; Cayan *et al*., 1999). It is affected by large, frontal storms in the winter season that produce intense rainfall basinwide (Singer and Dunne, 2004), although rainfall in the Sierra Nevada has generated the largest floods in the lower Sacramento River. Spring

Table I. Information on major Sacramento valley dams

Dam	Completed	Capacity (m^3)	Elev ASL (m)	Runoff
Folsom (F)	25/2/1955	1.2E + 09	142	2.3E + 09
New Camp Far West (CFW)	30/9/1963	1.3E + 08	79	2.3E + 08
Shasta (S)	30/12/1943	5.6E + 09	325	4.5E + 09
Whiskeytown (W)	1/5/1963	3.0E + 08	369	1.6E + 08
Oroville (O)	1/11/1967	4.4E + 09	274	2.5E + 09
Black Butte (B)	1/1/1963	1.8E + 08	130	1.0E + 08
New Bullards Bar (NBB)	1/1/1969	1.2E + 09	599	1.6E + 09

Information on dams including abbreviations, date completed, capacity, elevation and median annual runoff prior to dam construction.

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snowmelt does not generally produce flooding. Spring precipitation and runoff appear to be decreasing since 1940 with no change in annual totals, indicating a shift towards more intense winters of mostly rainfall runoff as a result of global climate change (Aguado *et al*., 1992; Dettinger and Cayan, 1995; Shelton, 1998; Knowles and Cayan, 2004).

The majority of floodwater in the lowland valley is diverted via a series of passive (no gates) weirs into a system of flood bypasses which function similar to natural conveyance floodplains by shunting flows directly to the Sacramento delta. Once these lateral weirs are overtopped, flow moves into engineered portions of the natural floodplain. This weir and bypass system, which predates the construction of dams on the Sacramento and its major tributaries, was constructed following the observation that the Sacramento River did not have the natural capacity to convey even frequent floods. Therefore, natural overflow channels in the floodplain were leveed for use in conveying floods through a smaller floodplain area and to prevent frequent development of an inland sea (Kelley, 1998) and to maximize floodplain reclamation for agriculture. Dams were installed between 1940 and 1970 (Table I) in the uplands to augment the existing flood control system, for power generation, and to provide water for various downstream uses. Many of the largest dams are located in the foothills of mountain ranges (elevation <600 m ASL, Table I) and were primarily designed to dampen the largest winter flood peaks and store spring snowmelt runoff for summer irrigation in the valley. The influence of each dam on downstream hydrology is measured in part by its impounded runoff index (*IRI*), defined here as the ratio of reservoir capacity to median annual flood runoff volume, a slight modification from the definition in Batalla *et al*. (2004). In addition to determining this value at gauging stations directly downstream of dams, I computed the numerator of this ratio as the additive upstream reservoir capacity for stations under the influence of multiple dams.

HYDROGRAPH ANALYSIS

I divided daily streamflow records from the US Geological Survey (USGS) at 10 gauging stations (Figure 1), downloaded from the World Wide Web available at http://nwis.waterdata.usgs.gov/usa/nwis/discharge (accessed June, 2004), into pre- and post-dam flow series before and after the date of completion of dam construction. Seven are located directly downstream of one of the major Sacramento basin dams (Table I) and three integrate the effect of multiple dams downstream of tributary confluences (Table II). Each has at least 7 years of daily streamflow data in both pre- and post-dam periods, but flow records at all stations average 31 pre-dam and 33 post-dam years of daily flow.

I excluded flow records from the year of dam construction at stations below a single dam and all flow records from the dam-building era at stations integrating the effect of multiple dams (Tables I and II). For example, flood records for Feather River @ Oroville exclude the period 1/10/1967–30/9/1968, which corresponds to the construction of Oroville Dam, and those for Feather River @ Nicholas (Figure 1) exclude the period 1/10/1962–30/9/1969, corresponding to the construction dates of the upstream dams, New Camp Far West (1963) and New Bullards Bar (1969) on the Bear and Yuba Rivers, respectively (Tables I and II). The post-dam period at Bend Bridge incorporates an interbasin water transfer from the Trinity River, which began in 1963 and increased mean annual flow by 15% (California Dept. of Water Resources, 1994), but has had no significant impact on flood flows.

I also analysed flow records from a control gauge unaffected by dams, Deer Creek, and divided them into pre- and post-dam data centred on the date 1/10/67, which roughly corresponds to the construction period of nearby Oroville Dam. I tested various centre dates to see if the resulting computations for this gauge are sensitive to this choice and they are not. Deer Creek lies between the Modoc plateau and the Sierra Nevada and is therefore a good representative of background climatic conditions in the basin. If there was any systematic difference in basin hydroclimate between the pre- and post-dam eras, it would be registered in the flood records at Deer Creek.

The resulting flow series were then used to compute empirical exceedence probability curves for six hydrograph characteristics: annual flow peak, annual flow trough (lowest value), annual flood volume, time to flood peak, drawdown time and interarrival time. The latter three characteristics describe the shape and timing of flood hydrographs, while the former three describe magnitude of the year's largest flood, low flow and the volume of flood water transported. These hydrograph characteristics are meant to be an indicatory sample from a large population of hydrograph features that could be affected by dams. The characteristics of hydrograph shape and timing were

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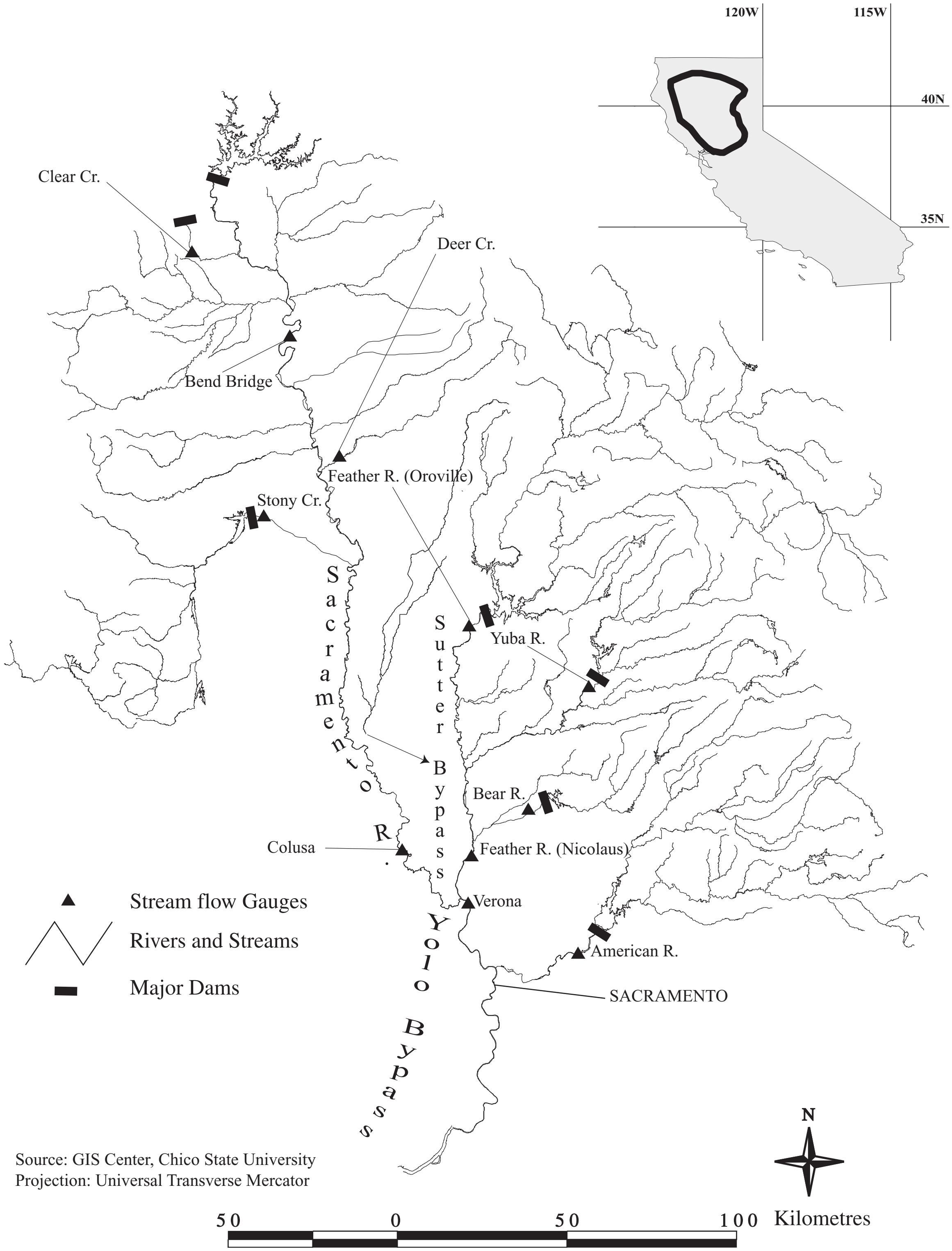

Figure 1. Map of study basin showing major dams, tributaries, bypasses and gauging stations. The bypasses function when floods overtop weirs along the Sacramento, shunting flow out of the Sacramento River. The shunting causes high flows to be asymptotic downstream of flood weirs (along the mainstem) because additional flow from upstream enters the bypass system

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Table II. Hydrologic stations

Station	Gauge #	Pre-dam	Base Q	Post-dam	Base Q	Upstream dams	IRI
American R. @ Fair Oaks (AR)	11446500	1/10/1904–30/9/1954	127	1/10/1955–30/9/2002	123	F	0.51
Bear R. nr Wheatland (BR)	11424000	1/10/1929–30/9/1963	17	1/10/1965–9/30/2002	19	CFW	0.56
Clear Cr. nr Igo (CC)	11372000	1/10/1940–30/9/1962	20	1/10/1963–30/9/2002	8	W	1.91
Deer Cr. nr Vina (DC)	11383500	1/10/1920–30/9/1967	11	1/10/1968–30/9/2002	14	None	
Feather R. @ Nicholas (FN)	11425000	1/10/1942–30/9/1962	292	1/10/1969–30/9/1983	314	CFW, O,NBB	1.49
Feather R. @ Oroville (FO)	11407000	1/10/1901–30/9/1967	209	1/10/1968–30/9/2002	47	O	1.77
Sacramento R. @ Colusa (CO)	11389500	10/1/1933–30/9/1943	216	1/10/1963–30/9/2002	364	S,W,B	1.39
Sacramento R. @ Verona (VE)	11425500	1/10/1933–30/9/1943	659	1/10/1969–30/9/2002	722	CFW,S, W,O,B, NBB	0.89
Sacramento R. nr Bend Br (BB)	11377100	1/10/1891–30/9/1943	453	1/10/1963–30/9/2002	417	S,W	1.23
Stony Cr. nr Orland (SC)	11388000	1/10/1955–30/9/1962	23	1/10/1963–30/9/1990	20	B	1.77
Yuba R. nr Smartville (YR)	11418000	1/10/1903–30/9/1940	101	1/10/1969–30/9/2002	84	NBB	0.75

Gauging station information including abbreviations, USGS gauge number, pre-dam flow recording period, pre-dam baseline discharge (m^3/s), post-dam flow recording period, post-dam baseline discharge (m^3/s), upstream dams (abbreviations in Table I) and impounded runoff index (upstream reservoir capacity divided by median annual runoff). Deer Creek (shaded) is the control station (no upstream dams).

computed using a flood threshold defined statistically by taking the mean of a curve that was obtained via locally weighted scatterplot smoothing (LOWESS) (Cleveland, 1979), a repeatable smoothing method which discounts the influence of large residuals. The implementation of LOWESS to define a flood threshold is described in Singer and Dunne (2004). Computations of hydrograph characteristics were made as follows: annual peak discharge as the highest daily mean discharge in a given year; annual flow trough as the lowest daily mean discharge in a given year; annual flood volume as the sum of daily mean flow above the flood threshold (baseline discharge in Singer and Dunne (2004) and Table II) for a given year; time to peak as the number of days between the flood threshold and the flood peak for every flood in a given year; drawdown as the number of days between the peak and the flood threshold for every flood in a given year and interarrival time as the number of days between each and every flood (i.e. equal to or less than the flood threshold) in a given year.

I plotted cumulative distributions for each hydrograph characteristic against empirical exceedence probability according to plotting positions without curve fitting. This method allows direct graphical and statistical comparison between pre- and post-dam hydrologic series, irrespective of length and concurrency of time period, and highlights anomalies in the shape of probability curves that indicate physical features of the watershed such as flood diversions (see below). It also encourages investigation of the entire distribution of hydrograph characteristics, instead of merely analysing a flow variable at a single recurrence interval. This method does not control for unusually wet or dry periods in a given era (pre- or post-dam). However, the length of flow records utilized herein provides a representative sample of the range of potential floods (Singer and Dunne, 2004). The use of the control gauge, Deer Creek, also enables recognition of obvious hydroclimate differences between eras.

I conducted two-tailed Kolmogorov–Smirnoff (K–S) tests to determine whether pre- and post-dam data for each characteristic at each station are drawn from the same distribution. To minimize incidents of Type I error (false positives), I used $\alpha = 0.01$, thus deriving a conservative estimate of change induced by dams. However, it should be noted that the K–S test is more sensitive to points at the median of the distribution that those at the tails (Zar, 1999). Therefore, differences indicated by the K–S test reflect systematic deviations between pre- and post-dam datasets rather than deviations that may be apparent at low exceedence probabilities, for example, which may indicate stochastic differences based on the flow record. However, I also provide assessments of differences in hydrograph characteristics at low and high exceedence probabilities derived from graphical comparison.

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RESULTS AND DISCUSSION

Comparisons of pre- and post-dam flow characteristics are presented in Figures 2–8 and Tables III and IV and are discussed below. Data for Deer Creek (control station) are presented in Figure 2. These latter hydrologic data illustrate that there are generally no statistically significant differences between data in the pre- and post-dam eras at the control station for any of the six hydrograph characteristics analysed herein (Table IV). There are, however, a few prominent changes between eras that are evident in graphical comparisons particularly at low exceedence probabilities (EPs): increases in peak discharge and interarrival time and a decrease in drawdown. Marked differences at only low EPs can be safely attributed to stochastic differences between flow records.

Of larger concern is the apparently systematic decrease in drawdown rate at moderate EPs for the Deer Creek gauge, which may be a result of the aforementioned shift in precipitation from snowmelt to rainfall (Aguado *et al*., 1992; Dettinger and Cayan, 1995; Shelton, 1998; Knowles and Cayan, 2004), expressed either as a progressive loss of the sustained snowmelt flood recession or a faster flood recession due to a lower water table because of reduced snowpack. There are also small increases in peak and trough discharge (at moderate exceedence probabilities) and flood volume (at low exceedence probabilities) that are evident from graphical comparison. The increase in annual peaks in the post-dam period could be due to the shift toward large rainstorms early in the flood season, which would also lead to higher annual flood volume because rainfall-generated floods are less attenuated by the basin than snowmelt floods. The difference in trough discharge at Deer Creek is so small that it is not worth discussion.

There are no significant differences for any of the six characteristics, according to K–S tests ($\alpha = 0.01$) between the pre- and post-dam eras (Table IV). Therefore, it appears safe to assume that climatic factors affecting hydrology have not changed between the pre- and post-dam periods beyond the observations of others already discussed. It is worth noting that I have not analysed flood timing (e.g. Julien day), which has been shown to have changed in the Sacramento basin in recent decades (Aguado *et al*., 1992; Dettinger and Cayan, 1995; Shelton, 1998; Knowles and Cayan, 2004).

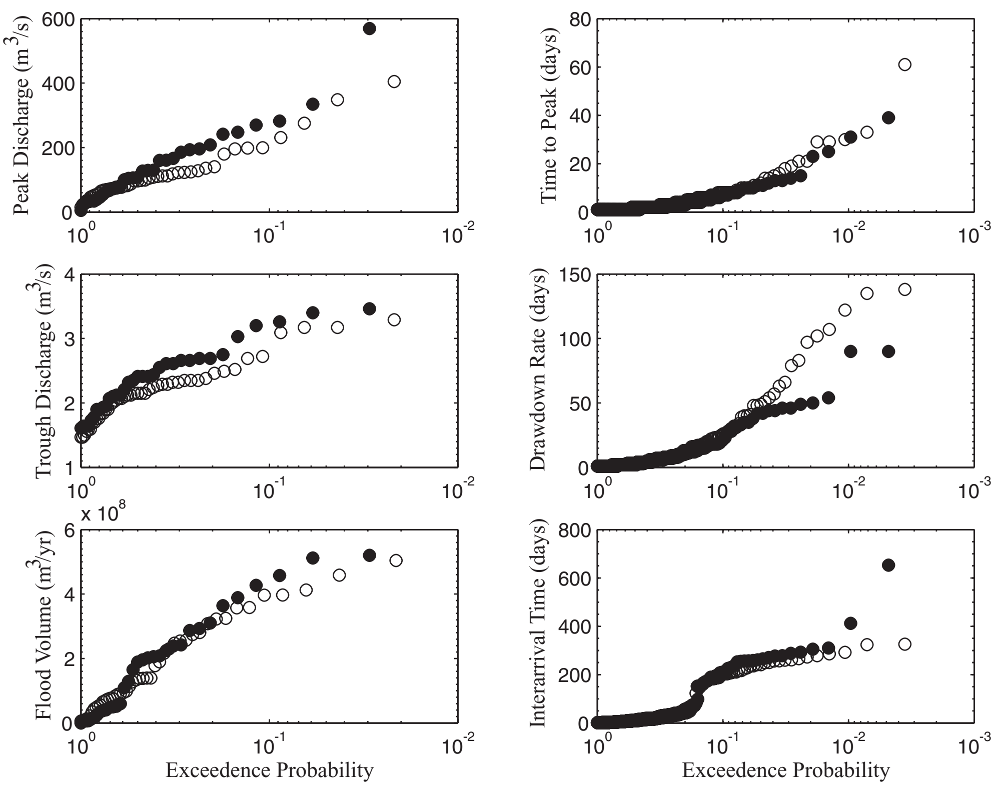

Figure 2. Hydrograph characteristics at Deer Creek (Figure 1) before and after the construction of Shasta Dam (Table I). Deer Creek is the control gauging station because there are no upstream dams. There are no statistically significant differences ($\alpha = 0.01$) between the pre- and post-dam eras for any of the hydrograph characteristics at Deer Creek

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Table III. Hydrograph characteristics affected by dams, post-dam: pre-dam

Station	High EP	Mid EP	Low EP	High EP	Mid EP	Low EP	High EP	Mid EP	Low
	Peak			*Trough*			*Volume*		
CC	$\downarrow$	$\downarrow$	$\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$
BB	$\downarrow$	$\downarrow$	$\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\sim$	$\sim$	$\uparrow$
DC	$\sim$	$\uparrow$	$\uparrow$	$\sim$	$\uparrow$	$\uparrow$	$\sim$	$\sim$	$\uparrow$
SC	$\downarrow$	$\sim$	$\downarrow$	$\sim$	$\downarrow$	$\downarrow$	$\downarrow$	$\sim$	$\downarrow$
CO	$\downarrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\sim$	$\uparrow$	$\sim$	$\sim$	$\uparrow$
FO	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
YR	$\downarrow$	$\sim$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$
BR	$\downarrow$	$\sim$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\sim$	$\sim$	$\uparrow$
FN	$\downarrow$	$\sim$	$\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\sim$	$\sim$	$\uparrow$
VE	$\downarrow$	$\sim$	$\sim$	$\uparrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\downarrow$	$\sim$
AR	$\downarrow$	$\downarrow$	$\sim$	$\uparrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\downarrow$	$\uparrow$
	Time to Peak			*Drawdown*			*Interarrival*		
CC	$\sim$	$\sim$	$\downarrow$	$\sim$	$\downarrow$	$\uparrow$	$\sim$	$\sim$	$\uparrow$
BB	$\sim$	$\sim$	$\downarrow$	$\sim$	$\uparrow$	$\downarrow$	$\sim$	$\downarrow$	$\uparrow$
DC	$\sim$	$\sim$	$\sim$	$\sim$	$\sim$	$\downarrow$	$\sim$	$\sim$	$\uparrow$
SC	$\sim$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\sim$	$\sim$	$\uparrow$	$\uparrow$
CO	$\sim$	$\sim$	$\downarrow$	$\sim$	$\downarrow$	$\downarrow$	$\sim$	$\uparrow$	$\sim$
FO	$\sim$	$\downarrow$	$\downarrow$	$\sim$	$\downarrow$	$\downarrow$	$\sim$	$\uparrow$	$\uparrow$
YR	$\sim$	$\uparrow$	$\uparrow$	$\sim$	$\uparrow$	$\uparrow$	$\sim$	$\sim$	$\uparrow$
BR	$\sim$	$\uparrow$	$\uparrow$	$\sim$	$\uparrow$	$\uparrow$	$\sim$	$\uparrow$	$\uparrow$
FN	$\sim$	$\sim$	$\uparrow$	$\sim$	$\sim$	$\uparrow$	$\sim$	$\sim$	$\uparrow$
VE	$\sim$	$\sim$	$\downarrow$	$\sim$	$\downarrow$	$\sim$	$\sim$	$\uparrow$	$\uparrow$
AR	$\sim$	$\uparrow$	$\downarrow$	$\sim$	$\uparrow$	$\downarrow$	$\sim$	$\uparrow$	$\uparrow$

Six hydrograph characteristics affected by dams. Table shows whether post-dam conditions for each station are greater than ($\uparrow$), less than ($\downarrow$) or approximately equal ($\sim$) to pre-dam conditions for high, middle and low exceedence probabilities (EP). Shaded rows indicate significantly different distributions (Table IV).

Although I recognize that river ecology may be affected by small changes in hydrology (e.g. Bullock and Gustard, 1992; Auble *et al*., 1994; Mahoney and Rood, 1998; Springer *et al*., 1999; Johnson, 2000), the following discussion will focus on large hydrologic changes that are evident in statistical and graphical comparisons between pre- and post-dam data. Furthermore, I will home in on comparisons at low and mid-range exceedence probabilities (the latter of which are measured by the K–S test), which represent the wetter (and drier) years and the larger floods in the record. These years and events are particularly relevant to flood control and to sediment transport and channel forming processes, which serve as physical boundary conditions for many ecological processes.

Annual peak flow

Peak flow, which quantifies the largest daily flow in a year, is significantly lower in the post-dam era at all EPs for Clear Creek, Sacramento River near Bend Bridge (hereafter referred to as Bend Bridge) and Feather River at Oroville (hereafter referred to as Feather @ Oroville), and is lower at high- and mid-level EPs at the American River gauge (Figure 3, Tables III and IV). Data for Clear Creek, Bend Bridge and Feather @ Oroville all show systematic decline in peak flow, which is reflected in high values of storage capacity and relatively high *IRI* for their upstream dams (Tables I and II). These factors indicate that most moderate and large flood peaks are completely stored behind Shasta, Whiskeytown and Oroville Dams for gradual release in the subsequent period. However, whereas storage capacity for Folsom Dam on the American River is also large ($>1.0 \times 10^9$ m^3), the runoff delivered to the dam from the Sierra Nevada is approximately double this capacity, resulting in low *IRI* at the American gauge (Figure 2). Folsom is thus only capable of controlling small and moderate flow peaks, a concern raised by a recent study investigating the flood risk on the American (National Research Council, 1995) and the continuing debate about the construction of a new flood control dam at Auburn.

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Table IV. Kolmogorov–Smirnoff test results, $\alpha = 0.01$

Station	n (pre, post)	Significant?	p-value	K–S statistic	Significant?	p-value	K–S statistic	Significant?	p-value	K–S statistic
		Peak			*Trough*			*Volume*		
CC	22, 39	Y	9.2E−06	0.6447	Y	2.3E−11	0.9231	Y	9.3E−04	0.5023
BB	52, 39	Y	7.0E−05	0.4676	Y	8.0E−05	0.4646	N	6.8E−01	0.1474
DC	47, 34	N	2.1E−01	0.2315	N	4.2E−02	0.3043	N	4.3E−01	0.1909
SC	7, 27	N	4.2E−01	0.3704	Y	1.5E−03	0.7963	N	3.5E−01	0.3704
CO	10, 39	N	1.7E−02	0.5385	N	2.2E−01	0.3675	N	7.2E−01	0.2333
FO	66, 34	Y	3.8E−07	0.5715	Y	9.2E−20	0.9692	Y	4.1E−07	0.5686
YR	37, 33	N	2.7E−02	0.3409	Y	1.5E−07	0.6667	N	2.5E−02	0.3432
BR	34, 37	N	2.2E−01	0.2432	Y	2.3E−06	0.6052	N	2.2E−01	0.2409
FN	20, 14	N	3.6E−01	0.3083	Y	1.8E−05	0.8045	N	5.8E−01	0.2571
VE	10, 33	N	6.9E−01	0.2525	Y	3.9E−06	0.9091	N	3.5E−01	0.3182
AR	50, 47	Y	7.6E−05	0.4477	Y	9.1E−20	0.9362	N	1.9E−02	0.3017
		Time to peak			*Drawdown*			*Interarrival*		
CC	22, 39	N	1.0E+00	0.0383	N	4.1E−02	0.156	N	7.4E−02	0.1439
BB	52, 39	N	3.3E−02	0.1181	Y	4.9E−04	0.1680	Y	8.0E−04	0.1630
DC	47, 34	N	3.8E−01	0.0819	N	1.5E−01	0.1029	N	2.4E−01	0.0928
SC	7, 27	N	1.8E−02	0.3114	Y	6.2E−03	0.3441	N	7.0E−01	0.1431
CO	10, 39	N	7.9E−01	0.0986	N	6.3E−01	0.1129	N	7.2E−01	0.1051
FO	66, 34	Y	3.2E−05	0.3549	Y	4.1E−03	0.2654	Y	9.5E−04	0.2953
YR	37, 33	N	4.6E−01	0.0958	N	9.9E−01	0.0469	N	4.9E−01	0.0933
BR	34, 37	Y	4.9E−03	0.2154	Y	8.0E−03	0.2066	N	7.5E−02	0.1593
FN	20, 14	N	9.7E−01	0.0826	N	9.2E−01	0.0933	N	3.6E−01	0.1556
VE	10, 33	N	5.8E−01	0.1557	N	1.9E−01	0.2166	N	5.3E−01	0.1616
AR	50, 47	Y	1.2E−08	0.3044	Y	2.9E−04	0.2077	Y	5.4E−03	0.1700

Kolmogorov–Smirnoff test results for six hydrograph characteristics affected by dams. Table contains the number of data points in each series compared in the pre- and post-dam eras, n (pre, post), whether the distributions are significantly different ($\alpha = 0.01$), the p-value and the Kolmogorov–Smirnoff statistic for each characteristic.

Other apparently systematic deviations between pre- and post-dam peak flows (Figure 3) are not significant according to the K–S test (Table IV), but deserve discussion. Most noteworthy, peak flow at the Sacramento River at Colusa (hereafter referred to as Colusa) appears to increase in the post-dam era, in spite of flood control by upstream dams. The annual peak flow exceedence probability curve at Colusa (and neighbouring station, Sacramento River at Verona-hereafter referred to as Verona) is asymptotic at low EPs, a matter that was described in Singer and Dunne (2004) as the result of an upstream flood diversion, Colusa Weir, which shunts high flows out of the mainstem Sacramento. That study also highlighted the role of bed erosion in the main channel near such flood diversions in increasing flow along the mainstem downstream of a lateral weir (figure 11 in Singer and Dunne, 2004), an effect that appears prevalent at Colusa. In other words, the weirs may become impaired by local erosion of the mainstem channel bed or deposition near the weir, to the extent that the partitioning of flow changes between the bypass and the mainstem, favouring more flow passing the weir and moving downstream in the main channel. Indeed impairment of Colusa Weir, due to a change in channel alignment, was documented by Kresch (1970).

Although pre- and post-dam flow peaks for the Yuba River and Bear River gauges are generally on par at low EPs, the New Years flood of 1997 overwhelmed the capacity of New Bullards Bar and New Camp Far West Dams, resulting in flood peaks at the lowest EP that exceed the largest in the pre-dam hydrologic records (Figure 3). Peaks at the Feather River at Nicholas gauge (hereafter referred to as Feather @ Nicholas), near the Sacramento confluence, appear to be primarily influenced by Yuba River and Bear River at high and mid-level EPs and by Feather @ Oroville at low EPs. However, this influence does not propagate to the Verona gauge on the mainstem Sacramento (nor does the relatively small weir effect observed at Colusa Weir), where there are no observed changes in annual flow peaks. The lack of influence inherited from Colusa or Feather @ Nicholas and registered at Verona is at least partially explained by the upstream Fremont Weir, which shunts off a large percentage of flood

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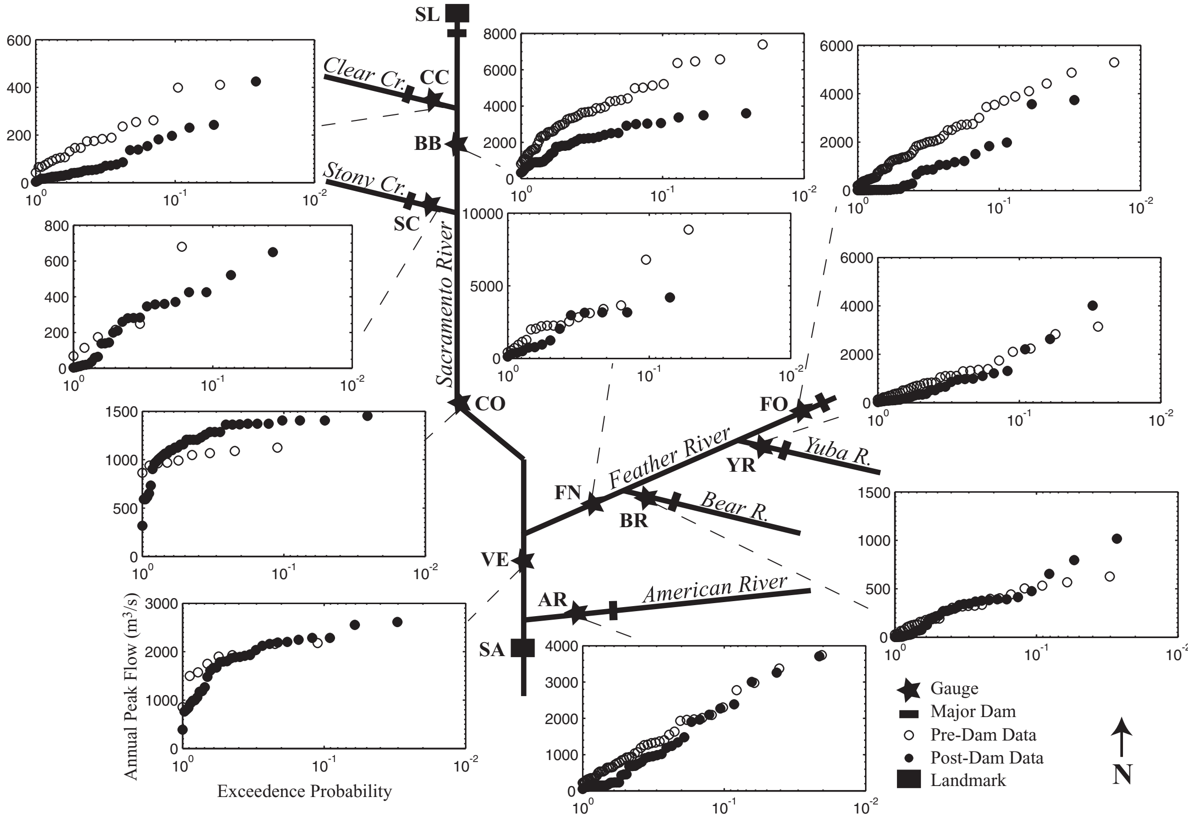

Figure 3. Map of annual peak flow probability including study area limits: Shasta Lake (SL) and Sacramento (SA). Station abbreviations from Table II

flow (c.f. additive flow from CO and FN with that at VE for a given EP in Figure 3). This is also reflected in the low *IRI* computed for Verona compared with the values computed for Colusa and Feather @ Nicholas (Table II).

In general, large flood control dams in the Sacramento basin decrease peak flow directly below the dam, but do not control floods in the lower Sacramento River, where the least frequent floods are just as large (or larger) than pre-dam ones. The city of Sacramento instead relies primarily on the valley bypass system to keep it from flooding.

Annual trough flow

Annual trough flow, an indicator of low flow conditions, is significantly higher in the post-dam era than in the pre-dam era at all EPs for Clear Creek, Bend Bridge, Feather @ Nicholas, Yuba River, Bear River, American River and Verona and is significantly lower for Stony Creek and Feather @ Oroville (Figure 4, Tables III and IV). The large increase in trough flow below most dams is reflective of their role in provision of irrigation and water supply and the generation of hydroelectricity in the summer season. This effect propagates through the Feather River and the Sacramento downstream of the Feather confluence, where irrigation water is required in high volumes for rice fields in the flood basins abutting these rivers. However, the Sacramento River at Colusa shows no inheritance of increased trough flow from upstream because of the high concentration of irrigated fields upstream of this station that are served by the Glenn-Colusa Irrigation District canal, from which flows are diverted out of the Sacramento River between Bend Bridge and Colusa.

More unusual are the increases in trough flow at Stony Creek and Feather @ Oroville, both of which have relatively large values of *IRI*, indicating the flood control role of upstream dams. One would expect these dams to also elevate summer trough flows for hydroelectricity generation, water supply and irrigation. However, this is not

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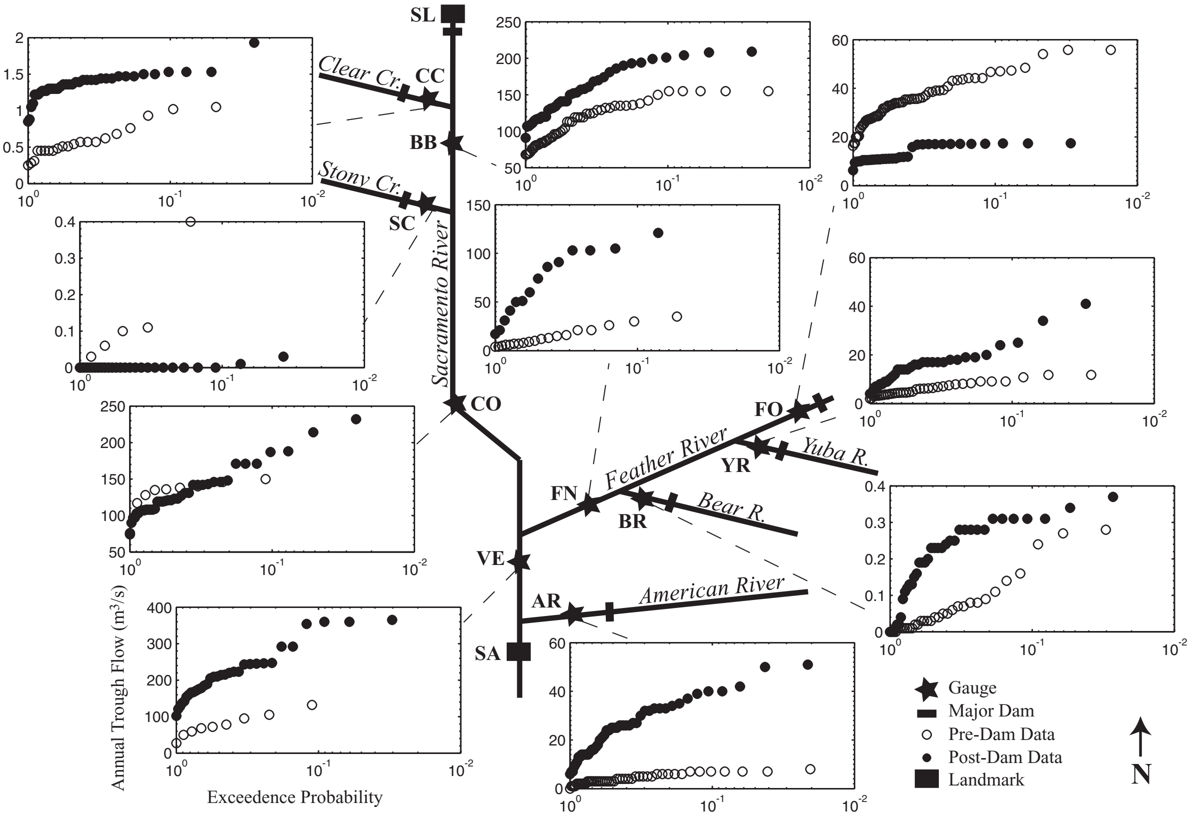

Figure 4. Map of annual flow trough probability including study area limits: Shasta Lake (SL) and Sacramento (SA). Station abbreviations from Table II

evident in the flow record. Summer flows trapped by Oroville Dam are generally diverted to the San Joaquin Valley and to southern California for irrigation and water supply, which actually reduces the summer trough flow for Feather @ Oroville. Likewise, summer flows trapped by Black Butte Dam are generally rerouted via the Glenn-Colusa Irrigation District canal (upstream of the Stony Creek gauge) to supply irrigation water to farmers in the surrounding basins.

In general, most dams in the valley increase annual flow trough because of high summer flow releases for multiple uses. The influence from the Sierra Nevada propagates through the lower Sacramento River, although the effect from the upper Sacramento River (upstream of the Feather confluence) does not. Water transfers out of the valley cause net decrease in downstream flow troughs.

Annual flood volume

Annual flood volume (*AFV*), a measure of all waters discharged during floods, significantly decreases at all EPs between pre- and post-dam eras for Clear Creek and Feather River at Oroville (Figure 5, Tables III and IV). These stations have the highest *IRI* values of all, indicating the strong influence of the upstream flood control dams. Since the upstream reservoirs are able to sequester almost twice the annual runoff, much of the flood water is stored and released (below the flood threshold) in the summer season for other purposes. However, it is not completely clear why, except at the lowest pre-dam EP, no such pattern exists for Stony Creek, which has an *IRI* value equal to that of Feather @ Oroville. One possible explanation is that the long growing season on the west side of the Sacramento Valley (March to November) promotes the release of flood flow before the end of the flood season.

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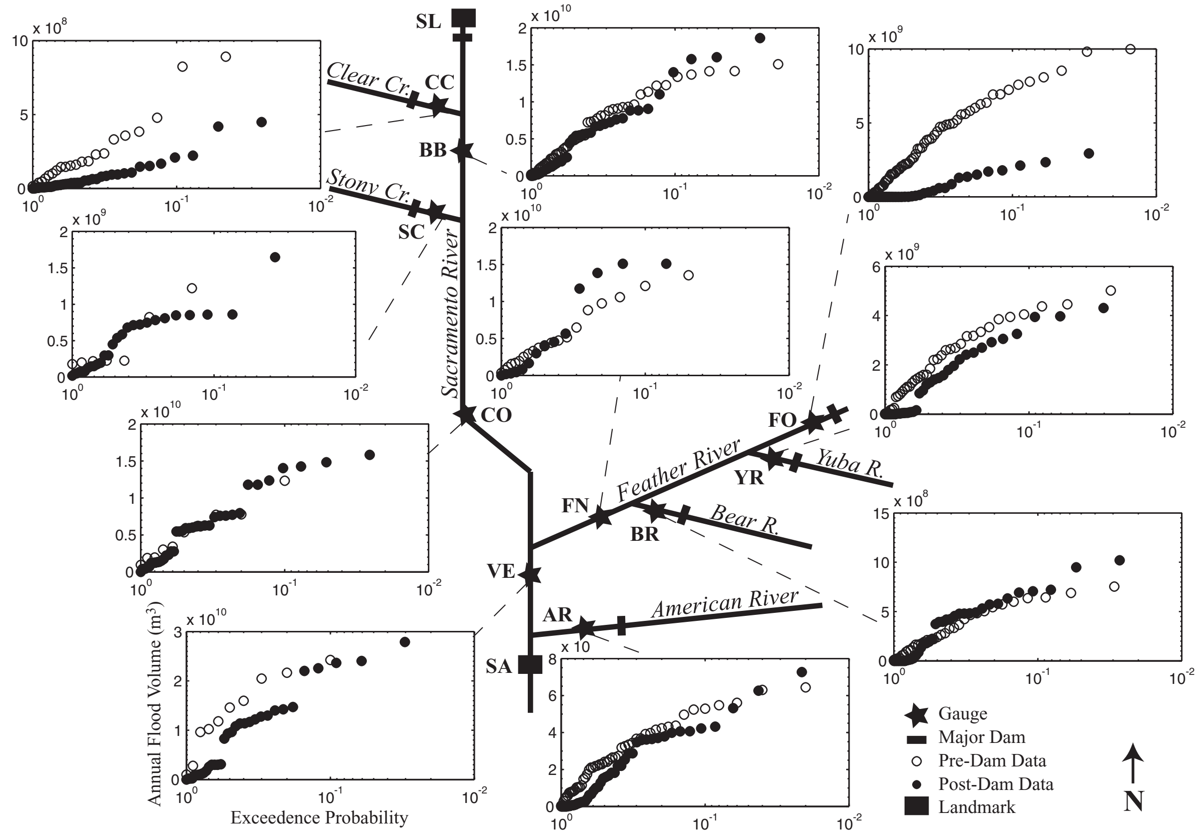

Figure 5. Map of annual flood volume probability including study area limits: Shasta Lake (SL) and Sacramento (SA). Station abbreviations from Table II

Other apparently systematic deviations between pre- and post-dam peak flows (Figure 5) are not significant according to the K–S test (Table IV), but deserve attention. *AFV* increases at low EPs for Bend Bridge and Bear River, similar to the pattern at the Deer Creek control gauge (Figure 2), suggesting the impact to these gauges may be merely the result of hydroclimatic changes (i.e. a shift toward more rainfall-runoff from snowmelt). A similar trend is evident for Feather @ Nicholas, which apparently inherits the signal from Bear River. Flood volume decreases slightly at most EPs for Yuba River, American River and Verona, which for the latter suggests a relative increase in flood flow over the upstream Fremont Weir, as pointed out in Singer and Dunne (2004), for all but the highest *AFV* years. Although Yuba and American River gauges have relatively low *IRI* (Table II), their upstream dams, New Bullards Bar and Folsom, are capable of storing floodwaters from the latter half of the flood season and releasing them for hydroelectricity generation and irrigation in the dry season, which explains the systematic decrease in *AFV* for these stations at all EPs.

Flood control operation generally causes decreased *AFV* in the post-dam era for stations with high *IRI* and for stations with moderate *IRI* and high storage capacity because flows can be stored until the end of the flood season. However, these influences rapidly dissipate to undetectable levels through the river network, possibly due to the contribution of smaller undammed tributaries, and they are mitigated by an apparent background signal of increasing *AFV* for low exceedence probabilities (Figure 2).

Time to peak

Time to peak (*TTP*), which describes hydrograph shape before the flood peak, is significantly different between pre- and post-dam eras for Bear River, Feather @ Oroville and American River (Figure 6, Tables III and IV). At

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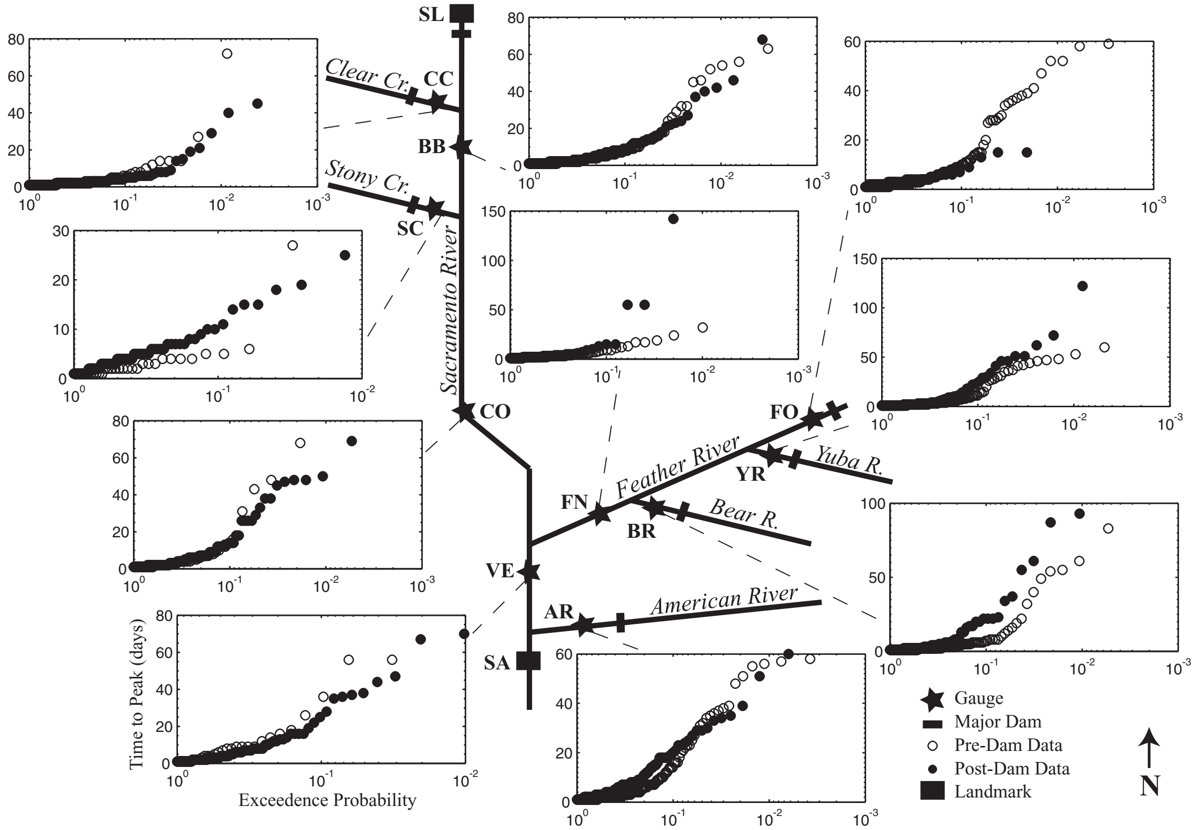

Figure 6. Map of time to peak probability including study area limits: Shasta Lake (SL) and Sacramento (SA). Station abbreviations from Table II

middle and low EPs, there is an increase in *TTP* for Bear River and a decrease for Feather @ Oroville, while *TTP* for American River increases at middle EPs and decreases at low EPs in the post-dam eras. An increase in *TTP* generally results from an extension of the rising limb of the hydrograph by early flow release in anticipation of a flood. The releases continue on a gradually increasing basis to control the peak flow, an operational practise that reduces the flood peak and is prevalent at dams with low *IRI* (e.g. Bear and American Rivers, Table II), due to relatively limited flood storage capacity. However, this strategy appears to be ineffective for low EPs on the American River below Folsom Dam (Figure 6), perhaps because large floods on the American completely overwhelm Folsom Dam, as previously discussed. The decline in *TTP* for Feather @ Oroville is a result of intensive flood control (only possible where *IRI* is high) that completely cuts off flood peaks (evident from Figure 3 and Table III) by storing the water for the entire flood period. In this case, there is no extension of the rising limb; in fact, it is shorter because the peak is lower.

Other noteworthy yet statistically insignificant differences are evident from graphical comparisons and markedly distinct from the patterns observed at the Deer Creek control gauge, which registers no apparent change in *TTP*. *TTP* during moderate and long floods for Stony Creek and Yuba River is systematically longer in the post-dam period for reasons similar to those for Bear and American Rivers (i.e. early flow releases). However, this seems to be a curious operational strategy for the Black Butte Dam above Stony Creek because of its high *IRI*. A possible explanation is that water from small floods early and late in the flood season is diverted out of Stony Creek via the Glenn Colusa Irrigation District Canal located downstream of the dam, which is reasonable because of the long growing season in the region. Such diversions would stretch the hydrograph (e.g. longer rising limb) and increase *AFV* with no change in peak (c.f. Figures 3, 5 and 6).

The *AFV* data for Bend Bridge suggest that Shasta Dam is operated to completely cut off the large flood peaks and shorten the rising limb, but a single extreme point at the lowest EP for the post-dam era points to early release

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operation for the largest floods (Figure 6). Feather @ Nicholas apparently inherits the early flow release signal from the Bear and Yuba gauges. However, this signal does not propagate into the lower Sacramento River, which is consistent with the decrease in flood volume at Verona (Figure 5). The data at Verona actually mimic the pattern recorded at Colusa, which in turn appears to mimic Bend Bridge. However, considering the large number of tributaries entering the Sacramento River between Bend Bridge and Colusa, an alternative explanation for *TTP* declines for Colusa and Verona at low EPs is the weir impairment effect discussed above, which would lead to more rapid flood conveyance through the mainstem (~20 days faster for the longest floods), instead of producing the slower rising limb that would be expected downstream of a major flood diversion.

Generally, *TTP* declines where flood control operations completely cut off peaks and increases where dams extend the rising limb of the hydrograph using early release operation. The declines in *TTP* appear to propagate through the river system, but their interpretation is partially complicated by the effect of flood diversions.

Drawdown time

Drawdown time (*DT*), which characterizes hydrograph shape after the flood peak, is significantly different between the pre- and post-dam eras for Bend Bridge, Stony Creek, Feather @ Oroville, Bear River and American River (Figure 7, Tables III and IV). *DT* declines for Bend Bridge and Feather @ Oroville at moderate and low EPs because of the complete cutoff of large flood peaks, a downstream effect that is only possible below a dam with relatively high *IRI* (Table II). Similar to the discussion for *TTP*, such an operational scheme shortens the falling limb and releases water storage after the flood period.

Bear River, Stony Creek and American River all register significant increases in *DT* (Table IV). The Bear River gauge recorded longer *DT* for most EPs, suggesting extended flow releases at the upstream New Camp Far West

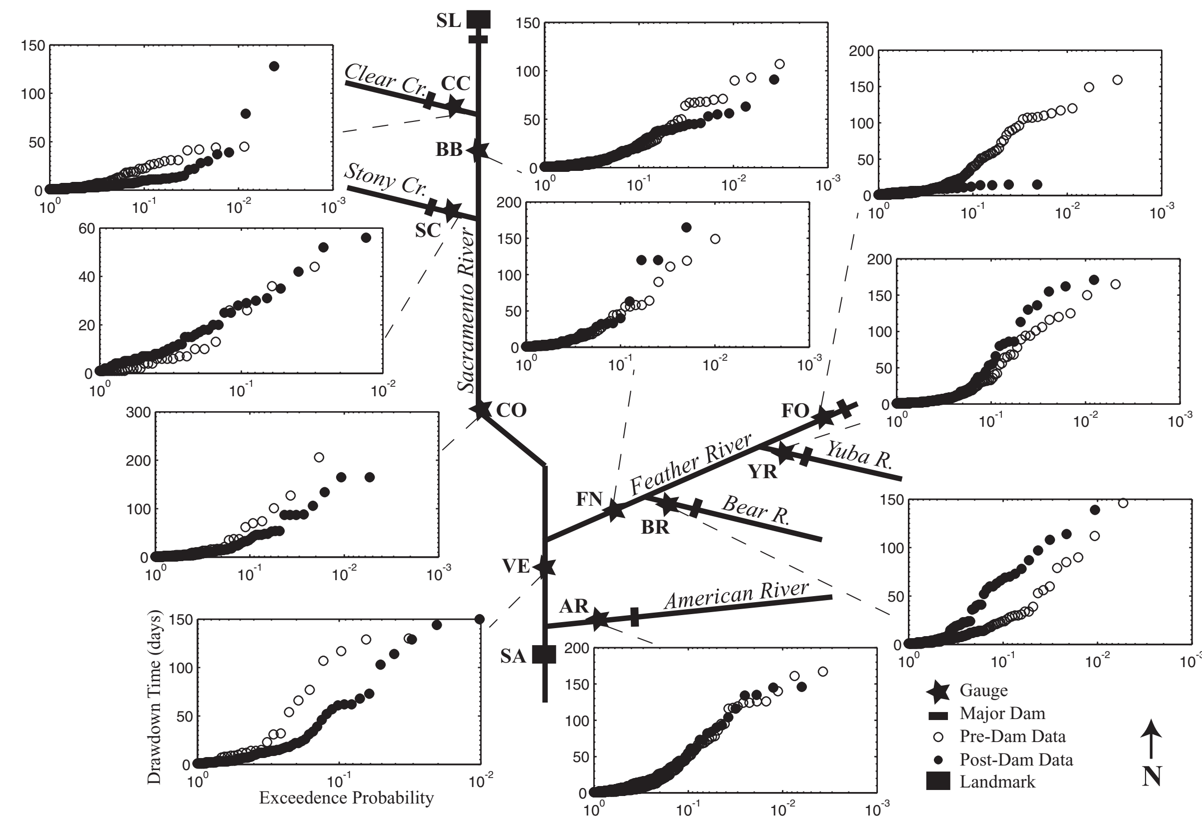

Figure 7. Map of drawdown time probability including study area limits: Shasta Lake (SL) and Sacramento (SA). Station abbreviations from Table II

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Dam to damp out peaks for all but the smallest floods. Similar operational strategies appear to be in effect at Black Butte and Folsom Dams, which control floods on Stony Creek and American River, respectively. However, because of its high *IRI*, this flood control strategy seems unnecessary for Stony Creek. It is more likely that the increase in drawdown at this gauge is reflective of irrigation practices that utilize flows from early and late season floods. Releasing flow for irrigation at these times would increase *DT*, effectively stretching the falling limb by a few days (Figure 7), as well as lengthening the rising limb (Figure 6) and increasing the *AFV* (Figure 5), while maintaining the same flood peak (Figure 3). However, this practise does not continue for floods with extremely long drawdown times, which are representative of large floods in the middle of the flood season when irrigation is unnecessary. The data for the American River suggest falling limb extension for all but the longest flood recessions, which probably correspond to the largest flood peaks Folsom Dam is ill-equipped to control (Figure 3) because of its low *IRI* (Table II).

There are other graphical differences in pre- and post-dam drawdown worth discussing. Because Deer Creek (the control gauge) recorded a decrease in *DT* at medium and low EPs, there is real possibility of hydroclimatic change that is perhaps due to a lower water table because of smaller snowpack, which was discussed previously. This would tend to shorten drawdown, which is observed at Clear Creek (at moderate EPs), Colusa (at moderate and low EPs) and Verona (at moderate EPs). Clear Creek annual peak, *TTP* and *DT* data suggest that during the largest floods, peaks are cut off by Whiskeytown dam thus shortening the rising limb, but the falling limb is lengthened by extended late releases (Figures 3, 6 and 7). Shortened *DT* at Colusa and Verona appears to propagate from Bend Bridge to the lower Sacramento River. However, it is also possible that erosion near flood diversions limits flow over weirs and induces faster flood conveyance through the mainstem, although this breaks down at Verona for the lowest pre-dam EP, perhaps due to the influence of the Feather River. Yuba River *DT* is higher at moderate and low EPs and this influence (combined with that from Bear River) appears to propagate to the Feather @ Nicholas gauge.

DT generally declines where flood control operations completely cut off peaks and increases where dams extend the falling limb of the hydrograph using late release operation. The declines in *TTP* appear to propagate through the river system, but their interpretation is partially complicated by the effect of flood diversions.

Interarrival time

Interarrival time, a specification of the time between floods, is significantly different between the pre- and post-dam eras for Bend Bridge, Feather @ Oroville and American River (Figure 8, Tables III and IV), with longer interarrival at middle and low EPs for Feather @ Oroville and American River and shorter interarrival at mid-level EPs for Bend Bridge. Longer interarrival time results from complete control of small (and moderate) floods. This effect increases the difference between pre- and post-dam interarrival at low EPs at most stations (and indeed at Deer Creek, Figure 2), indicating a post-dam increase in the length of the dry season, as previously discussed. It is not clear how dams could shorten interarrival times (e.g. at Bend Bridge), other than by chance. However, an alternate possibility is flow releases above the flood threshold between floods to create reservoir space for flood retention.

All stations studied exhibit graphically (but not statistically) longer interarrival times at low EPs, a consistent natural phenomenon throughout the basin that perhaps indicates an impact of global climate change on flood arrival. This general effect is especially apparent for the lowest EP at all stations, suggesting a sharp increase in the length of the extreme dry period. The prospect of such a hydroclimate change in the Sacramento has broad implications for irrigation, water supply and salinity in the Bay-Delta (Knowles and Cayan, 2002, 2004; Dettinger and Cayan, 2003). The increases evident at moderate EPs for Stony Creek, Yuba and Bear Rivers, suggest the effect of controlling small and moderate floods, which is likely superimposed on the background change in hydroclimate.

It is not clear whether and to what extent the increase in interarrival time below dams propagates through the network. However, Feather @ Nicholas records higher interarrival only for low EPs (as opposed to the moderate EP effect depicted for the upstream gauges, Figure 8), conveying the impression that only the background hydroclimatic signal affects interarrival at this station. And records for Colusa and Verona show very little change in interarrival at comparable EPs. However, post-dam interarrival at low EPs increases abruptly, which again signifies the basinwide background signal.

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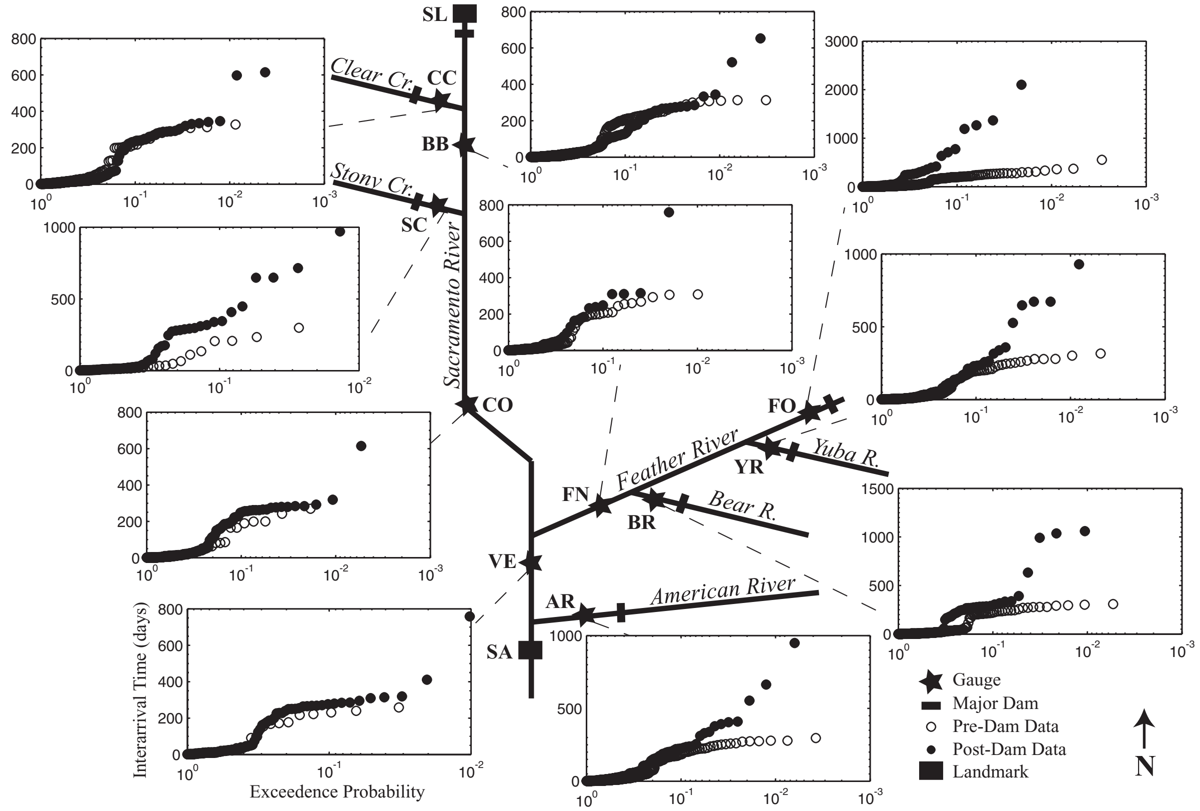

Figure 8. Map of interarrival time probability including study area limits: Shasta Lake (SL) and Sacramento (SA). Station abbreviations from Table II

In general, a shift in basinwide hydroclimate (perhaps resulting from global climate change) appears to have increased the length of extremely dry periods. This effect is accentuated at moderate EPs by dam operations that completely control small and moderate floods.

Further discussion

It is obvious that the largest dams have the largest local downstream impact on hydrology. However, their influence on local hydrographs fades very rapidly with distance downstream and with the confluence of tributaries. Feather @ Nicholas, which is under the influence of three upstream dams, generally inherits hydrograph characteristics from Bear and Yuba Rivers, whose combined annual flood runoff makes up only about two-thirds of that at Feather @ Oroville (Table I). Feather @ Oroville has a large *IRI* value which both limits the propagation of its hydrograph characteristics and ensures that *IRI* at Feather @ Nicholas is also high (Table II).

The Colusa and Verona stations are not very influenced by the hydrograph characteristics at upstream stations, except perhaps with respect to hydrograph shape. However, it is difficult to discern upstream dam influence from the effects of upstream flood diversions. Colusa and Verona are both positioned downstream of major flood weirs which shunt high flow into a system of bypasses and are located far downstream of flood control dams. These two factors conspire to produce floods of similar magnitude and interarrival times in the pre- and post-dam eras at both stations. The important implication here is that because dams are not effective at controlling floods in the lower Sacramento River, the floodplain communities along the lower Sacramento must rely heavily upon a weir and bypass system that was designed and built more than 70 years ago.

Major dams influence downstream hydrology in complex ways that are largely a function of operational rules designed to benefit multiple water uses including flood control, irrigation, power generation, water supply and

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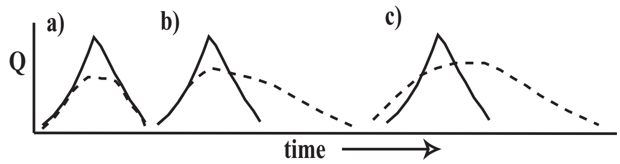

Figure 9. Idealized view of three types of flood control, where (a) peaks are cut off and stored with no change in time to peak or drawdown, (b) peaks are cut off and accommodated by prolonged falling limb releases (early release) and (c) peaks are cut off and accommodated by anticipatory flow releases on the rising limb and prolonged falling limb releases (early and late release). Solid lines indicate original flood hydrographs and dashed lines represent dam releases

ecological restoration. *IRI* is a generally a strong indicator of the impact of flood control dams on flow characteristics such as annual peak, annual flow volume, time to peak and drawdown, but is less relevant to annual trough and interarrival time. Dams that have high storage capacity relative to annual flood volume (i.e. high *IRI*) are likely to cut off flood peaks and store them for subsequent release following flood termination (e.g. Shasta, Whiskeytown, Oroville). Such practise also reduces *TTP* and *DT* and lowers *AFV* because small and moderate sized floods are completely cut out of the hydrologic record. Dams with low *IRI*, on the other hand, do not have adequate storage capacity to completely cut off flood peaks. To control floods, they must instead be operated to lengthen the rising (early release) and falling (late release) limbs of the hydrograph (e.g. New Camp Far West, New Bullards Bar, Folsom). Generally, the hydrograph is extended on both limbs (increasing *TTP* and *DT*), but there are some late release dams (e.g. Black Butte), which lengthen the falling limb without affecting the rising limb (c.f. Figures 6 and 7). These three types of prevailing flood control operation in the Sacramento basin are depicted schematically in Figure 9.

The data at Deer Creek indicate a hydrological change in the post-dam era that is a potential impact of global climate change. Other authors have acknowledged a shift in precipitation from late-season snow to rain earlier in the season, which hastens the onset of the dry season (Aguado *et al*., 1992; Dettinger and Cayan, 1995; Shelton, 1998). The majority of this signal is imposed in the 1300–2700 m elevation range of the Sierra Nevada (Knowles and Cayan, 2004), which ensures the effect is registered in the flood records of stations downstream of Sierra foothill dams (Table I). The changes detected herein, expressed as declines in *DT* and interarrival time at low exceedence probabilities, corroborate the other research and are consistent for most of the stations analysed. The influence of flood control dams is superimposed upon this background hydroclimate signal, potentially exacerbating a basinwide problem. Recent work has pointed out that the loss of spring-summer flows from the Sierra cause high salinity in the Bay-Delta estuary and has projected changes in its annual salinity cycles (Knowles and Cayan, 2002, 2004; Dettinger and Cayan, 2003). This paper confirms their results via a separate set of gauging stations, suggests hydroclimatic changes in hydrograph characteristics that are not treated in larger models (e.g. Knowles and Cayan, 2002), and identifies the necessity of separating out natural/background hydroclimatic signals from those imposed by dam operation in this and other basin throughout the western United States (e.g. Stewart, 2005).

Flow alteration is commonly discussed as a strategy of river rehabilitation to optimize the magnitude, shape and timing of flood hydrographs for habitat benefit in major river systems. The analysis presented herein demonstrates that such a strategy should only be implemented with a detailed investigation of the local, downstream and network impacts of dam re-operations, particularly in managed basins with a variety of installed flood control and diversion structures. For example, in addition to identifying a target habitat and its flow requirements (e.g. frequency of sediment transporting flows, timing of salinity reducing flows), it is important to track the influence of such a change through the fluvial system to limit unintended consequences and ensure maximum benefit to the system as a whole.

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