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4 authors, including:

P.H.A.J.M. Van Gelder
Delft University of Technology

Zhi-jun Dai
East China Normal University

Zhenghong Tang
University of Nebraska at Lincoln

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RESEARCH ARTICLE

Impact of dams on flood occurrence of selected rivers in the United States

Xuefei MEI[1,2], P.H.A.J.M. VAN GELDER[2], Zhijun DAI (✉)[1], Zhenghong TANG[3]

1 State Key Laboratory of Estuarine & Coastal Research, East China Normal University, Shanghai 200062, China
2 Faculty of Technology, Policy and Management, Delft University of Technology, 2628BX Delft, the Netherlands
3 Community and Regional Planning Program, University of Nebraska-Lincoln, Lincoln, NE 68588-0105, USA

Abstract A significant large number of dams have been constructed in the past two centuries in the United States. These dams' ability to regulate downstream flooding has received world-wide attention. In this study, data from 38 rivers distributed over the entire conterminous Untied States with extensive pre- and post-dam annual peak discharge records, were collected to research the impacts of various dams on the flood behaviors at a national scale. The results indicate that dams have led to significant reductions in flood magnitude for nearly all of the sites; the decrease rate in the mean of annual peak discharge varies between 7.4% and 95.14%, except for the Dead River, which increased by 1.46%. Because of dams' effectiveness, the probability density curve of annual peak flow changes from a flat to peaked shape because both the range and magnitude of high discharges are decreased. Moreover, the potential impact of dams on flood characteristics were closely related to the dam's geographic location and function, the ratio of the storage capacity of the dam to the mean annual runoff of the river (C/R), and the ratio of reservoir storage capacity to the area of its drainage (C/D). Specifically, the effects of dams on annual peak flows were more related to latitude than longitude. Compared with dams built for other purposes, the dam exclusively used for flood management cut off more flood peaks. Increases in the ratios of C/R and C/D increased the degree of modification of annual maximum discharge.

Keywords flood characteristics, river discharge, dam, flood modification

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E-mail: zjdai@sklec.ecnu.edu.cn

1 Introduction

Dams, as the most common infrastructure for water control, provide valuable social and economic benefits for people living nearby, including irrigation, hydropower generation, water supply and flood protection. The World Commission on Dams (2000) has reported that at least 45,000 large dams (15 meters or higher) have been built around the world since the 1930s. Nearly 50% of the world's rivers are regulated by at least one dam somewhere along their reaches.

It is widely accepted in the scientific literature that dams and their impounded water reservoirs can significantly modify river hydrology in the downstream reaches, including flow, sediment, temperature, biological and physical condition (Kondolf, 1997; Richter et al., 1996; Nilsson et al., 2005; Kileshye Onema et al., 2006; Walling, 2006; Zhang et al., 2006; Dai et al., 2008; Dai and Liu, 2013). Modifications of river flow patterns may also affect ecological and morphological changes in downstream rivers, estuaries, and coastal waters (Huang, 2010; Biria et al., 2015; Xie et al., 2015). Dams' induced hydrological modifications have manifested themselves particularly in high flow events, such as flood peaks and annual maximum daily discharge. For instance, when analyzing the Ebro River and tributaries in northeastern Spain, Batalla et al (2004) concluded that the magnitude of floods had been reduced in most rivers and found that the impacts of dams depend on the index of reservoir capacity to mean annual runoff. Mathias Kondolf and Batalla (2005) compared dam impacts on 14 regulated rivers in the Sacramento-San Joaquin River system in Californian and showed that 2-year flows decreased by 53% and 81% in the Sacramento and San Joaquin River basins, respectively. Assani et al. (2006) detected alterations in the annual maximum flows after dam construction for all regulated rivers in Quebec that were investigated, and indicated that the degree of modification was related to the type of regulated hydrologic regime and watershed size. On the other hand, Chen et al. (2001) suggested that the occurrence of major discharge peaks in the Yangtze River system became more frequent between 1950 and 1980, when a large number of dams were built on the upper reaches of the Yangtze River basin. By far, most of our knowledge on the hydrological impacts from dams remains context-specific (McManamay, 2014). However, relatively little work has been undertaken to investigate the influence of dams on flood characteristics over a larger scale, such as at a national and global scope. Magilligan et al (2003) had developed a scale-independent assessment of the hydro-geomorphic impacts of 21 dams across the United States based on the data until 2000. Over the past 15 years, newly available data make it is possible to reassess the influence of dams on rive hydrology. A larger number of dams can be included in the research to provide more accurate and comprehensive results. It has been predicted that climate changing scenarios may lead to an acceleration of the global hydrological cycle, and, in particular, an increase in flood risk (Milly et al., 2002; Held and Soden, 2006; Villarini et al., 2011), which further promotes the necessity of national as well as global knowledge of how dams influence flood characteristics. Accordingly, decision makers can understand the possible links between dam regulation and flood risks, and take timely action. The magnitude of benefits and impacts is significant in countries with extensive large dam infrastructure, like the United States. We believe this enhanced understanding of dams' effectiveness will also have important value to other countries, most notably developing countries with dense populations.

Over the past two centuries, more than 8100 large dams have been constructed in the United States; a large number of multipurpose reservoirs with considerable storage capacity were built in the 1950's, '60's, and '70's (Graf, 1999). Meanwhile, the annual peak flow of many rivers in the contiguous United States exhibited significant changes over the past century (Changnon and Kunkel, 1995; Lins and Slack, 1999; Douglas et al, 2000; Juckem et al, 2008). In such a circumstance, it is of great significance to evaluate the linkage between dam regulation influence and flood behavior variations in the United States.

Therefore, rivers in the continental United States that are regulated by dams were used as study cases in this paper. The primary objective was to assess how dam construction has altered floods over the downstream reach of the dam. To comprehensively understand the effect of dams on flood characteristics, probability density curves for pre- and post-dam peak discharge series were derived. Moreover, the primary driving factors that may influence the impact of dam on flood behaviors were discussed.

2 Data and methods

2.1 Data collection and processes

In this study, three criteria were used to select river basin and related flow series within the United States. Firstly, the length of the flow records should be long enough to reflect changes to the river over time, and frequency analysis was used for sites with over 20 years of pre- and post-dam measurement series (Batalla et al, 2004). Secondly, the gauging station should be downstream of and close to the dam. In this way, the comparisons between pre- and post-dam series can represent the influence of the dam on flood behaviors. Thirdly, the river basin should be free from other kinds of significant anthropogenic effects, such as channel dredging, sand mining, and land use, to ensure that dam regulation is the primary human activity in the river basin.

Thirty-eight rivers that satisfied the above requirements were selected to comparatively analyze the influence of dams on high flow series, which can reflect the general behavior of most rivers in the conterminous United States. Among the 38 study cases, all of the rivers have post-dam annual average flow records, 36 rivers have pre-dam annual average flow records, and 28 rivers are available for frequency analysis. Because of its large size, the United States includes a wide variety of climate types.

In general, the contiguous USA can be grouped into six regions according to their climatic features. The Pacific Northwest (PN) lies in the wettest part of the country, with scattered rain showers occurring throughout the year. The Mid/South Pacific (MSP) enjoys excellent weather year round, with generally dry and pleasant summers and tolerable winters that seldom experience snow. The Midwest (MW) is moderately dry, with precipitation mainly in late spring and early summer. The Northeast (NE) experiences moderate rain, with heavy snow and freezing rain in winter. The Southeast (SE) has moderate rains evenly throughout the year while the Southwest (SW) is the hottest region of the USA, with heavy rains and thunder storms in the eastern portions of the range.

The 38 study rivers cover the six different climate regions described above. Detailed information and reference numbers for each dam are presented in Table 1, and Fig. 1 describes their geographical locations. The dam data were taken from the National Inventory of Dams web site (https://nid.usace.army.mil). An initial review of the dams showed that most construction occurred between the 1950s and the 1970s (26 of 38). Twelve of these dams were exclusively intended for flood control, 14 dams were built partly for flood control, and the remaining 12 serve for other purposes. The drainage areas for the 38 dams range from 41 km^2 (the Wynoochee River (WA)) to 322,800 km^2 (the Missouri River (NE)). The earliest record of annual peak discharge dates back to 1895 (Smokey Hill River (KS), while the most recent record is from 2013.

The annual peak discharge series for the study sites, part of which are shown in Fig. 2, were obtained from a U.S. Geological Survey web site (http://water.usgs.gov/waterwatch/). It should be noted that over the 38 river catchments, most of the data sets can be divided into two sub-periods at some point in time. Before the change point,

Table 1 Description of the study dams

No.	River/Creek (State; Climate type)	Dam/s	φ/(°)	λ/(°)	Purpose	Drainage area/km^2	Finish year	Period	Annual runoff /(10^7m^3)	Capacity /(10^7m^3)
1	Bill Williams (AZ; SW)	Alamo	34.23	– 113.60	FC	4,770	1968	1929 – 2013	8	174
2	Colorado (AZ; SW)	Glen Canyon	36.94	– 111.48	H	108,355	1963	1921 – 2013	1475	369
3	White (AR; SE)	Bull Shoals	36.37	– 92.57	H/FC	23,400	1951	1928 – 2013	2332	710
4	Trinity (CA; MSP)	Trinity	40.80	– 122.76	H/WS	692	1960	1912 – 2013	147	341
5	Prosser (CA; MSP)	Prosser Creek	39.38	– 120.14	FC/I	52.9	1962	1942 – 2013	7	4
6	Natchaug (CT; NE)	Mansfield Hollow	41.76	– 72.18	FC	174	1952	1931 – 2013	26	6
7	Chattahoochee (GA; SE)	West point	32.92	– 85.19	FC	3,380	1974	1897 – 2013	502	75
8	Etowah (GA; SE)	Allatoona	34.14	– 84.64	FC/H	7,510	1950	1938 – 2013	161	45
9	South Fork Boise (ID; MSP)	Anderson Ranch	43.36	– 115.45	H/I	978	1950	1943 – 2013	63	62
10	Deadwood (ID; MSP)	Deadwood	44.29	– 115.65	I	109	1931	1926 – 2013	19	19
11	Kaskaskia (IL; MW)	Carlyle	38.62	– 89.35	FC	2,717	1966	1930 – 2013	172	157
12	Wabash (IN; MW)	Huntington North	39.58	– 111.26	I	1,768	1966	1923 – 2013	129	1
13	Iowa (IA; MW)	Coralville	41.72	– 91.53	FC	3,115	1958	1903 – 2013	131	52
14	Smokey Hill (KS; MW)	Cedar Bluff	38.79	– 99.88	FC/I	7,580	1951	1895 – 2013	20	55
15	Sabine (LA; SW)	Iron Bridge	32.81	– 95.91	WS	8,229	1960	1923 – 2013	637	205
16	Dead (ME; NE)	Long Falls	45.19	– 70.31	WS/FC	516	1950	1939 – 1982	67	32
17	Westfield (MA; MW)	Knightville	42.29	– 72.86	FC	162	1941	1910 – 2013	28	8
18	South Fork Flathead (MT; MSP)	Hungry Horse	48.34	– 114.01	I/H/FC	1,640	1952	1911 – 2013	294	443
19	Missouri (NE; MW)	Fort Randall	43.06	– 98.56	FC/H	322,800	1953	1929 – 2013	2649	700
20	Little Humboldt (NV; MSP)	Chimney	41.40	– 117.18	WS	1,030	1974	1921 – 2013	2	4
21	Roanoke (NC; SE)	Kerr;Roanoke;Gaston	36.48	– 77.67	FC/H	8,400	1955	1912 – 2013	756	415
22	Ashuelot (NH; NE)	Surry Mountain	43.00	– 72.31	FC	420	1941	1907 – 2013	57	5
23	Delaware (NY; NE)	Downsville	42.08	– 74.91	WS	784	1954	1912 – 2013	149	53
24	James (ND; MW)	Jamestown	46.93	– 98.71	FC/I	2,820	1954	1928 – 2013	6	28
25	Olentangy (OH; NE)	Delaware	40.36	– 83.07	FC	386	1948	1911 – 2013	32	16
26	Arkansas (OK; SW)	Robert S. Kerr	35.35	– 94.85	H	74,460	1964	1925 – 2013	590	54
27	North Santiam (OR; PN)	Detroit and Big Cliff	44.72	– 122.25	FC/I/H	438	1953	1921 – 2013	290	56
28	Malheur (OR; PN)	Warm Springs	38.72	– 123.01	I	1,100	1919	1909 – 2013	20	21
29	Crooked (PA; NE)	Crooked Creek	40.72	– 79.51	FC	277	1940	1910 – 1991	36	16
30	Saluda (SC; SE)	Lake Greenwood Buzzard Roost	34.17	– 81.90	FC	1,360	1940	1926 – 2013	191	1
31	Rapid (SD; MW)	Deerfield	44.03	– 103.79	I	322	1947	1929 – 2013	5	2
32	Leon (TX; SW)	Belton	31.10	– 97.48	FC	3,560	1954	1924 – 2013	57	231
33	Tennessee (TN; SE)	Normandy	35.47	– 86.24	FC	481	1976	1935 – 2013	75	15
34	Pound (VA; SE)	Flannagan	37.23	– 82.35	FC/WS	221	1963	1926 – 2013	23	18
35	Cowlitz (WA; PN)	Mayfield	46.50	– 122.59	H	1,400	1963	1927 – 2013	556	23
36	Wynoochee (WA; PN)	Wynoochee	47.39	– 123.61	FC/WS	41	1973	1952 – 2013	80	9
37	Belle Fourche (WY; MSP)	Keyhole	44.32	– 104.77	I/FC	3,248	1952	1947 – 2013	8	40
38	Weber (UT; MSP)	Wanship	40.79	– 111.41	FC/H/I	335	1957	1951 – 2013	20	8

Notes: For dam type: FC –flood control; WS –water supply; H – hydroelectric; I – irrigation. For dam location: φ – latitude; λ – longitude.

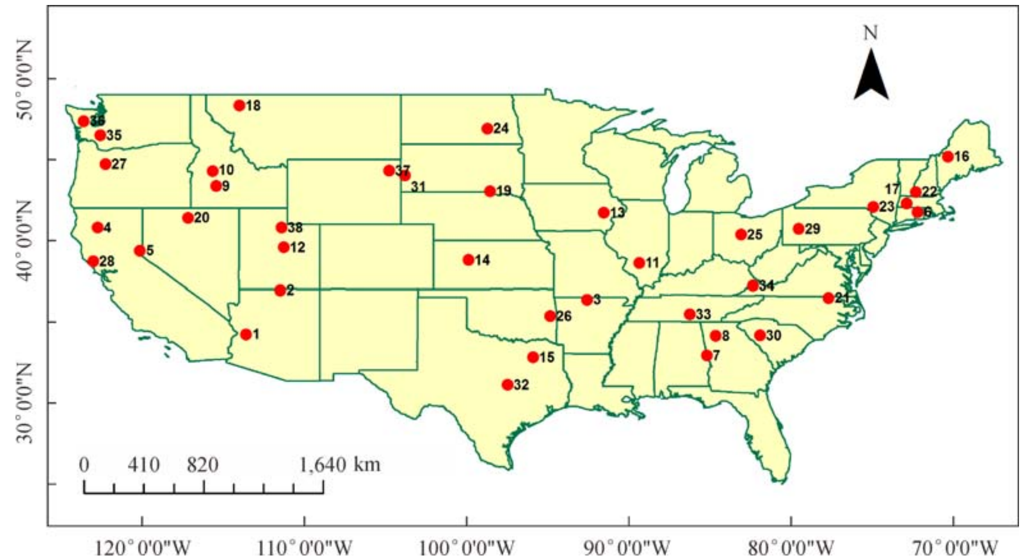

Fig. 1 Locations of the study dams.

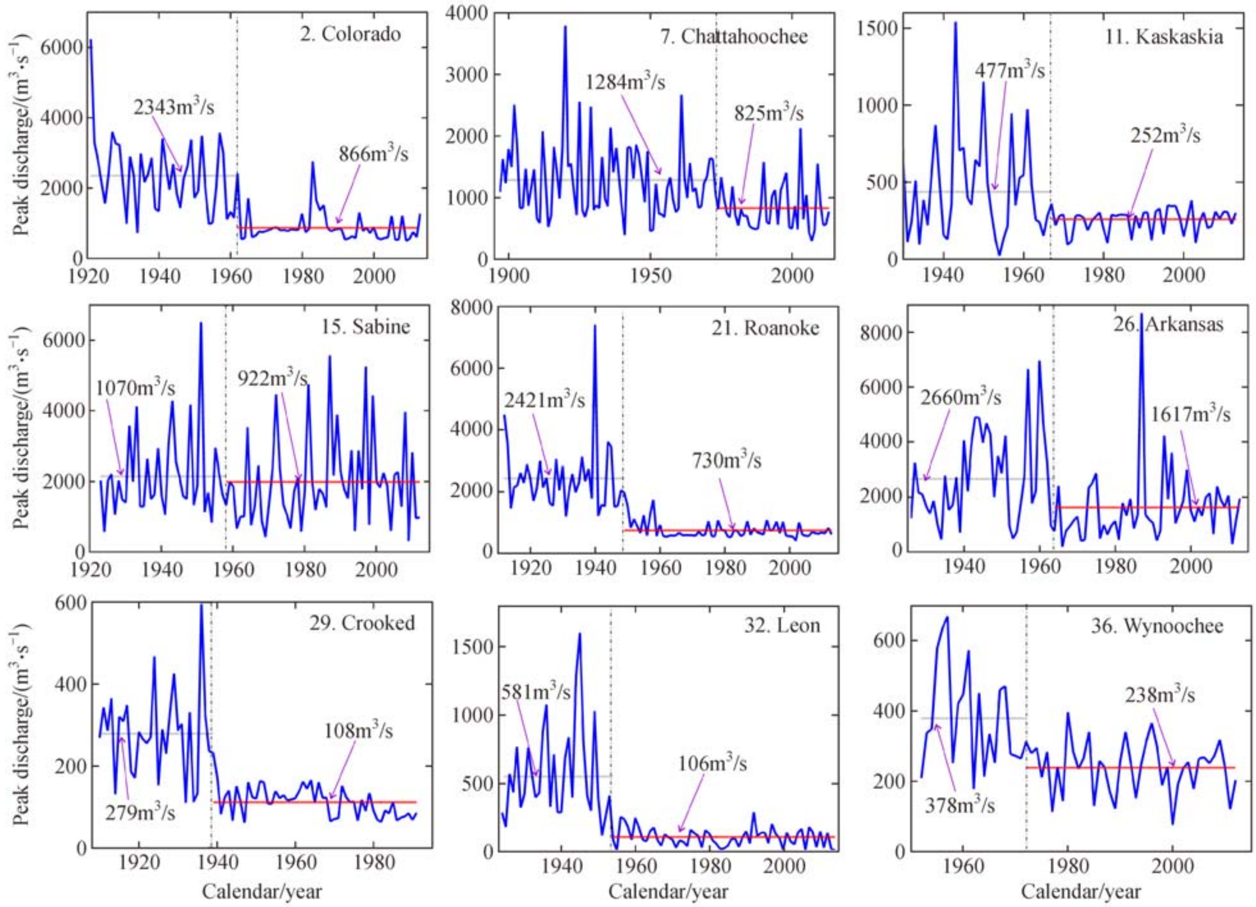

Fig. 2 Annual peak discharge series from 9 representative river gauge stations, with the dotted line showing the year of dam construction.

the data series have larger amplitudes with larger mean values, while after that they are more stable, and the data have smaller mean values.

2.2 Methods

2.2.1 Trend and change point analyses

The identification of major changes in the annual peak discharge series is of considerable interest for this research (Graf, 2006; Wang et al., 2011). Many statistical tests have been developed to investigate the homogeneity of time series (Perreault et al., 2000; Hess et al., 2001; Reeves et al., 2007; Bormann et al., 2011). Two statistical tests, the non-parametric Mann–Kendall test (MK) (Kendall, 1975) and the parametric standard normal homogeneity test (SNHT) (Alexandersson and Moberg, 1997), are used in this paper to identify the presence of slow change over time (trend analysis) and the occurrence of abrupt change (change point), respectively.

The Mann–Kendall test is a widely used non-parametric method that account for trends in data. The MK statistic S is defined as follows:

$$S=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\mathrm{sgn}(x_j-x_i), \tag{1}$$

where x_i and x_j are sequential data series with i = 1,2,3,…, $n-1$ and $j = i+1, i+2, i+3,\ldots,n$, n is the sample size, and

$$\mathrm{sgn}(\theta)=\begin{cases}+1 & \theta>0\\ 0 & 0\\ -1 & \theta<0\end{cases}. \tag{2}$$

Mann (1945) has stated that when $n \geqslant 8$, the statistic S follows an approximately normal distribution with mean

$$\mathrm{E}(S)=0;$$

and variance

$$\mathrm{Var}(S)=\frac{n(n-1)(2n+5)-\sum_{i=1}^{n}t_i(t_i-1)(2t_i+5)}{18}, \tag{3}$$

where t_i is the number of ties to extent sample i. The standardized test statistic Z_{MK} is given by

$$Z_{MK}=\begin{cases}\dfrac{S-1}{\sqrt{Var(S)}} & S>0\\ 0 & S=0\\ \dfrac{S+1}{\sqrt{Var(S)}} & S<0\end{cases}. \tag{4}$$

The null hypothesis, that there is no trend, will be accepted at a significance level of 0.05 if the absolute value of Z_{MK} is less than 1.96.

SNHT compares the mean of the first a years of the records with that of the last $n-a$ years based on the statistic T_0, which is defined as follows:

$$T_0=\max_{1\leqslant a<n}T_{(a)}=\max_{1\leqslant a<n}\left(a\bar{z}_1^2+(n-a)\bar{z}_2^2\right),$$

$$a=1,2,\ldots,n, \tag{5}$$

where

$$\bar{z}_1=\frac{1}{a}\sum_{i=1}^{a}\frac{(Y_i-\overline{Y})}{s};\ \bar{z}_2=\frac{1}{n-a}\sum_{i=a+1}^{n}\frac{(Y_i-\overline{Y})}{S}. \tag{6}$$

$\overline{Y}$ is the mean, s is the standard deviation, and n is the length of the data set.

When T_0 approaches a maximum value at year $a = A$, a possible shift may have occurred at year A. The null hypothesis, that there is no sudden break at year A, is true if T_0 is less than the critical value T_c at a given significance level, which depends on the sample size (see Appendix, Table A1). As one of the classical parametric tests, the SNHT has the significant advantage of being efficient because it is able to make full use of all available information.

2.2.2 Probability distribution functions

In hydrology, future floods are predicted based on probability. By analyzing sample data, a probability distribution is identified and then used to estimate the likelihood of a future event. This function can take many forms, depending on the equations used to carry out the statistical analyses. The choice of an appropriate probability distribution for flood frequency analysis has long been of interest (Benson, 1968; Stedinger et al., 1993; Rao and Hamed, 2000). A series of distribution models, including Gumbel distribution, Weibull distribution, Pearson's distribution, generalized Pareto distribution, exponential distribution, inverse Gaussian, lognormal, and generalized logistic distributions, have been used in the literature (Ouarda et al., 1994; Van Gelder and Neykov, 1998; Malamud and Turcotte, 2006). In order to accurately generate flood quintiles with respect to various return periods for each river, generalized extreme value (GEV), lognormal (LN), Pearson type III (P-3), and Weibull (WBL) were adopted and compared in this paper. The commonly used maximum likelihood method (MLM) was applied to estimate the parameters for these mathematical models (Akaike, 1992; Frances et al., 1994). To assess the performance of each distribution, a Kolmogorov-Smirnov (KS) index, indicating the maximum difference between the empirical and theoretic frequencies, was calculated (Massey, 1951).

3 Results

3.1 Annual peak discharges

Based on the MK test, 25 study series have negative trends at the 5% significance level, 12 series have insignificant downward trends, and 1 series has an insignificant upward trend (Table 2). Meanwhile, the SNHT test detected statistically significant abrupt changes for 26 river basins, among which 24 coincided well with the years of dam establishments (Table 2). It can be expected that the abrupt variations in their annual peak flow series were closely

Table 2 Change test reports for the 38 river basins

No.	River/Creek	Z_{MK}	Downward trend	T_0	Significant change
1	Bill Williams (AZ)	−5.78	Significant	12.23	Y
2	Colorado (AZ)	−7.35	Significant	37.92	Y
3	White (AR)	−2.92	Significant	3.20	Y
4	Trinity (CA)	−4.34	Significant	29.83	Y
5	Prosser (CA)	−2.47	Significant	−5.10	N
6	Natchaug (CT)	−1.38	No	6.69	Y
7	Chattahoochee (GA)	−4.66	Significant	9.96	Y
8	Etowah (GA)	−5.04	Significant	28.48	Y
9	South Fork Boise (ID)	−3.67	Significant	−6.69	N
10	Deadwood (ID)	−2.27	Significant	−7.12	N
11	Kaskaskia (IL)	−2.78	Significant	8.99	Y
12	Wabash (IN)	−4.15	Significant	17.76	Y
13	Iowa (IA)	−2.56	Significant	1.18	Y
14	Smokey Hill (KS)	−1.45	No	−6.17	N
15	Sabine (LA)	−0.14	No	−7.40	N
16	Dead (ME)	−0.08	No	−7.07	N
17	Westfield (MA)	−4.87	Significant	15.43	Y
18	South Fork Flathead (MT)	−7.41	Significant	42.74	Y
19	Missouri (NE)	−3.36	Significant	17.40	Y
20	Little Humboldt (NV)	−1.34	No	−4.39	N
21	Roanoke (NC)	−7.61	Significant	51.01	Y
22	Ashuelot (NH)	−2.72	Significant	12.54	Y
23	Delaware (NY)	−0.83	No	−6.59	N
24	James (ND)	0.08	No	−6.56	N
25	Olentangy (OH)	−4.69	Significant	15.77	Y
26	Arkansas (OK)	−1.66	No	1.85	Y
27	North Santiam (OR)	−4.37	Significant	18.63	Y
28	Malheur (OR)	−0.37	No	16.49	Y
29	Crooked (PA)	−7.87	Significant	42.64	Y
30	Saluda (SC)	−2.88	Significant	3.43	Y
31	Rapid (SD)	−1.35	No	−5.31	N
32	Leon (TX)	−6.90	Significant	39.29	Y
33	Tennessee (TN)	−1.36	No	−1.91	N
34	Pound (VA)	−6.68	Significant	32.12	Y
35	Cowlitz (WA)	−4.31	Significant	0.08	Y
36	Wynoochee (WA)	−3.47	Significant	10.54	Y
37	Belle Fourche (WY)	−0.67	No	−6.91	N
38	Weber (UT)	−1.51	No	2.88	Y
	Percentage		65.79%		68.42%

related to the dam regulations. Furthermore, it is found that for the 24 dam-induced abrupt change rivers, 83.33% detected significant downward trends (Table 2). Accordingly, the decreased trends in annual peak flow series can also be attributed to the dam regulations. Moreover, the mean and standard deviation statistics for the annual flood peak series during pre- and post-dam stages are compared in Table 3. The results suggest significant reductions in the means for all sites except the Dead River. For 37 rivers, the mean decreased between 7.34% and 95.14%, while the

Table 3 Comparison of the mean and standard deviation between the pre- and post-dam time series

No.	River/Creek	Change in annual peak flow	
		Mean/%	Standard deviation/%
1	Bill Williams (AZ)	−95.14	−94.48
2	Colorado (AZ)	−63.05	−60.89
3	White (AR)	−27.81	−3.71
4	Trinity (CA)	−78.00	−73.22
5	Prosser (CA)	−33.64	−53.99
6	Natchaug (CT)	−25.40	−50.01
7	Chattahoochee (GA)	−35.71	−34.77
8	Etowah (GA)	−56.58	−79.20
9	South Fork Boise (ID)	−23.07	−24.38
10	Deadwood (ID)	−12.09	−26.55
11	Kaskaskia (IL)	−47.17	−77.77
12	Wabash (IN)	−43.15	−61.49
13	Iowa (IA)	−21.13	−23.08
14	Smokey Hill (KS)	−20.61	−42.43
15	Sabine (LA)	−7.34	5.48
16	Dead (ME)	1.46	70.53
17	Westfield (MA)	−58.12	−87.59
18	South Fork Flathead (MT)	−51.07	−46.28
19	Missouri (NE)	−45.70	−57.71
20	Little Humboldt (NV)	−53.64	−67.63
21	Roanoke (NC)	−69.84	−77.08
22	Ashuelot (NH)	−33.84	−49.29
23	Delaware (NY)	−10.53	28.48
24	James (ND)	−26.86	−32.43
25	Olentangy (OH)	−51.46	−91.73
26	Arkansas (OK)	−39.20	−18.84
27	North Santiam (OR)	−39.56	−40.06
28	Malheur (OR)	−67.47	−70.16
29	Crooked (PA)	−61.07	−68.10
30	Saluda (SC)	−46.94	−53.05
31	Rapid (SD)	−36.66	−27.92
32	Leon (TX)	−81.76	−81.55
33	Tennessee (TN)	−26.30	−46.92
34	Pound (VA)	−68.30	−87.29
35	Cowlitz (WA)	−26.36	17.73
36	Wynoochee (WA)	−37.10	−49.77
37	Belle Fourche (WY)	−23.89	103.05
38	Weber (UT)	−51.79	20.97
	Mean	−42.00	−39.82

mean for the Dead River increased 1.46%. In addition, the standard deviation decreased for 32 of the 38 river basins, and the standard deviation for the Sabine River, Dead River, Delaware River, Cowlitz River, Belle Fourche River, and Weber River increased (Table 3). For each flood peak series, the decrease in the mean and standard deviation was the result of dam regulation. When floods are expected, dams are used to store extra flow in the reservoirs; the water is released more slowly over a period of time at later dates to protect the downstream reaches.

3.2 Flood frequency

On the basis of the KS test results, the performance of each probabilistic distribution was described in terms of box plots, as shown in Fig. 3. For the pre-dam series, GEV was the favored statistical distribution, followed by LN and WBL. For the dam-regulated data, GEV was the best option, followed by LN and P-3. This conclusion is identical to that reached by Vogel and Wilson (1996). In addition, the four distribution functions indicate larger KS results for the post-dam series (Fig. 3). This means that the probability distributions are more suitable and accurate for random flow regimes in natural conditions.

According to the GEV analysis of the pre- and post-dam hydrologic observations, probability density curves can be derived for the data sets of interest, and flood quantiles can be calculated for given return periods. The probability density functions for part of the river time series that were derived from GEV are shown in Fig. 4. For the annual peak discharge under natural conditions, the probability density curve slopes down gently and uniformly to both sides with a flat top. Conversely, the dam regulated peak discharge series sharply peak and are usually accompanied with a long one-sided tail. In general, the performance of a dam and its reservoir on the probabilistic distribution reduce the number of high-frequency events and centralize the peak discharges over a relatively small range, which is consistent with the previous results shown in Table 3 on the reduction of the mean and standard deviation of the annual peak discharge series.

The GEV-determined estimates for 2-year, 5-year, 10-year, and 50-year floods are presented in Table 4. The analysis indicates that the effects of dam regulation are considerable, both on normal floods and on extreme events. The 2-year, 5-year, 10-year, and 50-year flood discharges were decreased by 41.34%, 44.87%, 46.22%, and 46.21%, respectively, following reservoir impoundment.

4 Discussion

4.1 The influence of climate change

In addition to dam regulation, flood variations may also be caused by climate change over the contiguous United States. Generally, natural floods in the United States are dominated by heavy rainfall, rapid snowmelt, or any combination thereof (Leathers et al., 1998; Ashley and Ashley, 2008). Geographically, in the western one-third of the contiguous United States, snow accumulation is the dominant factor in hydrologic floods, while in the eastern two-thirds, floods are highly correlated with heavy precipitation (Groisman et al., 2004).

Many studies have been implemented to quantify changes in extreme precipitation events over the conterminous United States; they show a national averaged

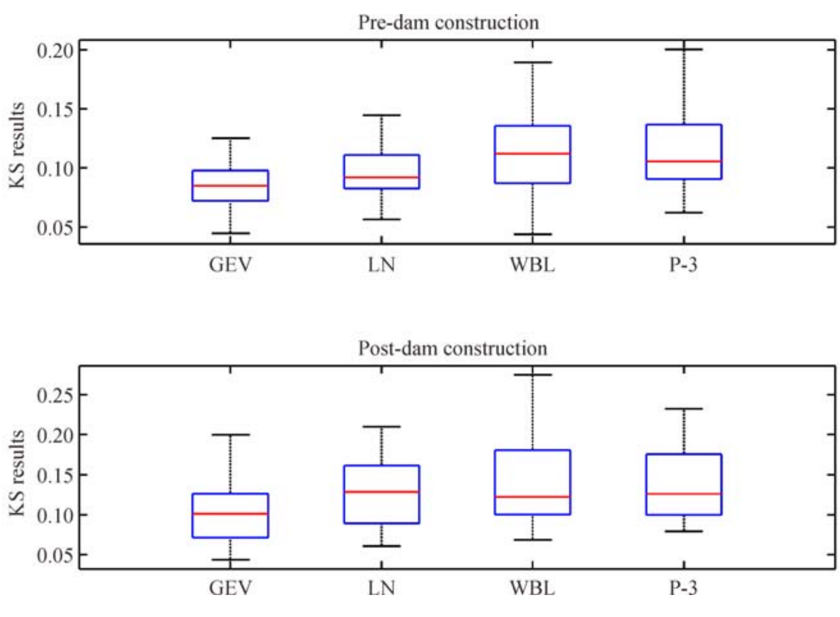

Fig. 3 Performance of probability distributions for pre- and post-dam time series. GEV: general extreme value distribution; LN: lognormal distribution; WBL: Weibull distribution; P-3: Pearson type III distribution.

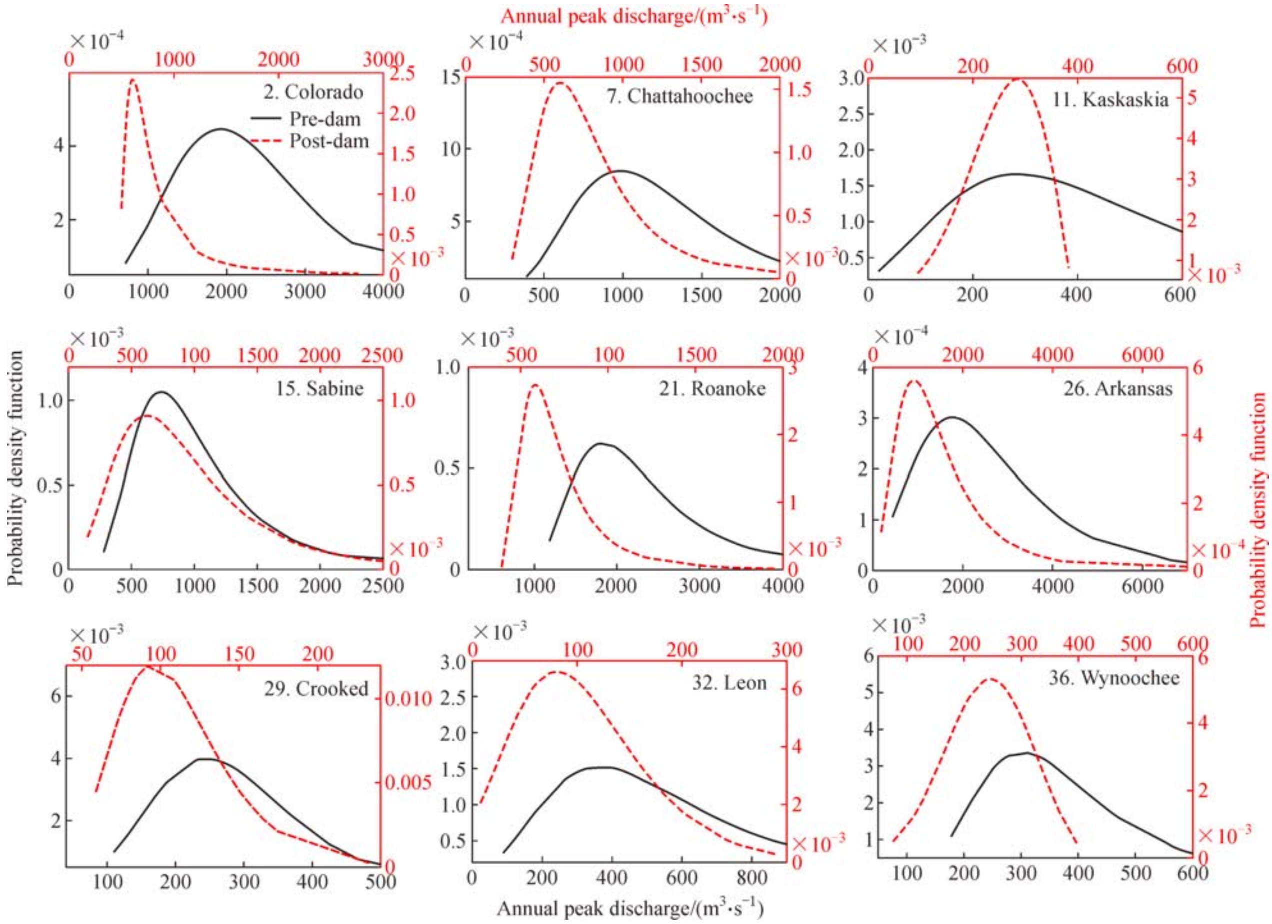

Fig. 4 Comparison of the probability density functions for the pre- and post-dam time series.

upward trend in the occurrence and intensity of extreme precipitation (Karl and Knight, 1998; Kunkel et al., 1999; Groisman et al., 2001; Kunkel et al., 2003; Janssen et al., 2014). For instance, compared to 1948 – 1978, up to 40% increase occurred in the frequency of days and multi-day rain events with extreme precipitations in the central United States during 1979 – 2009, when a large number of dams were constructed (Groisman et al., 2012). Meanwhile, a dominant and significant warming over most of the contiguous United States was found over the period of 1895 – 2011, with the largest change in winter months (Lund et a., 2001; Lu et al., 2005; Kunkel et al., 2013). For example, in the western one-third of the contiguous United States, where floods are mainly influenced by snow accumulation, the value of the temperature trend rate averages over 1.5ºC/century during 1898 – 2008, which may induce more snowmelt runoff (Capparelli et al., 2013). Taken together, significant increases in extreme precipitation and temperature occurred throughout the United States over the past decades. On the other hand, in the 38 study river basins, their annual peak floods had decreased by 42% on average due to the control of dams. Given such a circumstance, the effectiveness of dams to control flooding could be even stronger.

4.2 The influence of dam characteristics

Despite the general decline in the magnitude of floods, there were variations among the 38 rivers. The effects of the dams on the characteristics of the downstream floods varied greatly depending on a number of factors. Generally, the ability of a dam to regulate the downstream flood process is related to river hydrology and the dam's characteristic. This section discusses four impact parameters: geographic location of the dam, dam function, the ratio of the storage capacity of the dam to the mean annual runoff of the river (C/R), and the ratio of reservoir storage capacity to the drainage area (C/D). The change in the mean of annual peak discharge for each river is selected to link the above parameters with dam effects on flood control.

4.2.1 Dam location

As Table 3 indicated, the extent of dam-induced river flow changes varied from region to region, which can be attributed to the fact that responses of river hydrology to dam regulation are highly dependent upon watershed characteristics, such as local hydrology, soil and vegetation

Table 4 Comparisons of flood discharges under different return periods (m^3/s)

No.	River/Creek	Period	2-year	5-year	10-year	50-year
1	Bill Williams (AZ)	Pre	236.25	1142.05	3124.22	27995.83
		Post	7.22	68.24	306.09	8359.70
		D/%	–96.94	–94.02	–90.20	–70.14
2	Colorado (AZ)	Pre	2196.73	3104.92	3688.75	4926.37
		Post	739.38	1060.87	1406.98	2873.32
		D/%	–66.34	–65.83	–61.86	–41.67
4	Trinity (CA)	Pre	413.96	739.96	1022.60	1909.34
		Post	73.91	186.25	321.97	1000.83
		D/%	–82.14	–74.83	–68.51	–47.58
5	Prosser (CA)	Pre	15.13	33.68	60.86	242.07
		Post	11.81	26.62	45.31	144.94
		D/%	–21.97	–20.96	–25.55	–40.12
6	Natchaug (CT)	Pre	93.89	118.03	127.76	139.54
		Post	68.69	81.57	87.21	94.72
		D/%	–26.84	–30.89	–31.74	–32.12
7	Chattahoochee (GA)	Pre	1163.33	1677.89	2044.16	2928.91
		Post	724.91	1048.51	1306.80	2032.02
		D/%	–37.69	–37.51	–36.07	–30.62
11	Kaskaskia (IL)	Pre	399.03	687.51	905.27	1473.10
		Post	263.35	319.66	342.45	370.14
		D/%	–34.00	–53.50	–62.17	–74.87
12	Wabash (IN)	Pre	587.49	841.01	998.17	1316.37
		Post	341.92	439.59	501.03	627.77
		D/%	–41.80	–47.73	–49.80	–52.31
13	Iowa (IA)	Pre	310.11	494.95	626.08	941.48
		Post	242.81	361.92	451.06	680.90
		D/%	–21.70	–26.88	–27.95	–27.68
14	Smokey Hill (KS)	Pre	216.01	464.42	707.38	1606.85
		Post	212.72	389.51	523.17	872.50
		D/%	–1.52	–16.13	–26.04	–45.70
15	Sabine (LA)	Pre	925.80	1401.55	1773.37	2788.50
		Post	833.72	1371.45	1784.42	2886.11
		D/%	–9.95	–2.15	0.62	3.50
17	Westfield (MA)	Pre	179.15	300.26	410.70	781.91
		Post	96.90	120.07	133.16	156.77
		D/%	–45.91	–60.01	–67.58	–79.95
18	South Fork Flathead (MT)	Pre	697.93	910.99	1030.36	1243.52
		Post	328.43	438.26	517.00	708.98
		D/%	–52.94	–51.89	–49.82	–42.99
19	Missouri (NE)	Pre	3463.03	4944.95	6040.21	8818.58
		Post	1879.96	2658.59	3384.46	5899.02
		D/%	–45.71	–46.24	–43.97	–33.11
20	Little Humboldt (NV)	Pre	2.82	8.22	16.71	79.69
		Post	2.14	4.22	6.31	14.46
		D/%	–24.13	–48.72	–62.21	–81.86

(*Continued*)

No.	River/Creek	Period	2-year	5-year	10-year	50-year
21	Roanoke (NC)	Pre	2161.06	2977.57	3626.09	5434.97
		Post	669.98	872.26	1043.48	1563.50
		D/%	−69.00	−70.71	−71.22	−71.23
22	Ashuelot (NH)	Pre	182.96	258.06	309.18	425.76
		Post	124.00	162.49	188.25	245.70
		D/%	−32.23	−37.03	−39.11	−42.29
23	Delaware (NY)	Pre	688.06	955.88	1129.78	1503.11
		Post	560.62	861.31	1097.18	1744.32
		D/%	−18.52	−9.89	−2.89	16.05
24	James (ND)	Pre	19.19	44.50	73.30	205.37
		Post	15.57	33.60	52.23	126.67
		D/%	−18.85	−24.49	−28.75	−38.32
25	Olentangy (OH)	Pre	210.44	323.39	413.59	666.98
		Post	123.15	144.49	158.38	188.28
		D/%	−41.48	−55.32	−61.71	−71.77
26	Arkansas (OK)	Pre	2311.22	3802.08	4862.22	7419.76
		Post	1287.63	2215.00	2964.99	5107.76
		D/%	−44.29	−41.74	−39.02	−31.16
27	North Santiam (OR)	Pre	982.09	1365.65	1613.32	2141.32
		Post	598.96	811.74	951.82	1257.91
		D/%	−39.01	−40.56	−41.00	−41.26
29	Crooked (PA)	Pre	268.24	363.17	419.77	528.93
		Post	105.16	138.54	159.76	204.10
		D/%	−60.80	−61.85	−61.94	−61.41
32	Leon (TX)	Pre	491.93	810.78	1054.46	1700.40
		Post	96.97	156.28	192.99	267.19
		D/%	−80.29	−80.72	−81.70	−84.29
33	Tennessee (TN)	Pre	495.57	769.29	982.05	1558.73
		Post	408.79	573.37	681.45	916.88
		D/%	−17.51	−25.47	−30.61	−41.18
34	Pound (VA)	Pre	268.59	410.04	512.40	765.05
		Post	100.13	114.97	120.39	126.28
		D/%	−62.72	−71.96	−76.50	−83.49
35	Cowlitz (WA)	Pre	912.92	1211.84	1426.08	1948.21
		Post	614.83	936.77	1213.03	2067.75
		D/%	−32.65	−22.70	−14.94	6.14
36	Wynoochee (WA)	Pre	348.62	479.96	572.09	790.45
		Post	242.27	303.63	332.88	375.85
		D/%	−30.51	−36.74	−41.81	−52.45
	Mean	D/%	−41.34	−44.87	−46.22	−46.21

Note: D/% percentage of decrease between post and pre-dam discharge series

(McManamay, 2014). Therefore, the effect of dam location, expressed as latitude and longitude, on the extent of flood control in the United States was investigated. A three-variable, linear stepwise regression model was used to determine the modification in downstream peak flows with dam geographical location (Eq. 7):

$$Cp = -93.86 + 2.15*\mathrm{Lat} - 0.35*\mathrm{Long}(R = 0.45,\ P<0.01), \tag{7}$$

where Cp is the change in the mean of annual peak flood due to dam regulation (%), ranging from −95.14% to 1.46% (Table 3), and Lat and Long are the dam's latitude and longitude position, respectively. Because dams generally are built to store water upstream, Cp is negative.

It can be concluded from Eq. 7 that a dam's latitude has a much larger influence on Cp than its longitude. In addition, peak flood alteration is more severe at lower latitudes than at higher latitudes. For instance, the Leon River, being located at low latitude of 31.10°C, had an 81.76% reduction in mean discharge, while the Wynoochee River, in high latitude area of 47.39°C, only had a 37.10% decrease as a result of dam construction (Table 3). This may be related to the fact that low-latitude areas usually receive more precipitation and generate larger floods in wet seasons than high-latitude areas. Generally, a reservoir will produce a stronger regulation effect when it has higher possibility to store more water in flood season. This result agrees well with that of Magilligan et al. (Magilligan et al., 2003). Moreover, in addition to latitude, longitude can also affect the impacts of dams on annual flood peaks. For example, both the Bill Williams and the Saluda Rivers are located in low latitudes around 34°C; the Bill Williams River at high longitude suffered a severe decrease up to 95.14%, while the Saluda River at low longitude only indicated a medium reduction of 46.94% following dam regulations (Table 3).

4.2.2 Dam function and operation rules

A dam's function may significantly influence its effect on downstream discharge. Dams are built to store excess water during floods and release the flow according to their purpose. Specifically, dams built for flood control are designed to prevent or reduce flood damage to protect downstream areas. Dams built for power generation are designed to generate electric power for economic development. Dams built for irrigation are designed to store and release water to increase agricultural production. Dams built for water supply are designed to provide safe and adequate water for domestic, industrial, commercial, and other uses. A flood control reservoir will release water to the main stream immediately after a flood. The other three types of reservoir store water for a significant period of time and release it according to the demand. Accordingly,

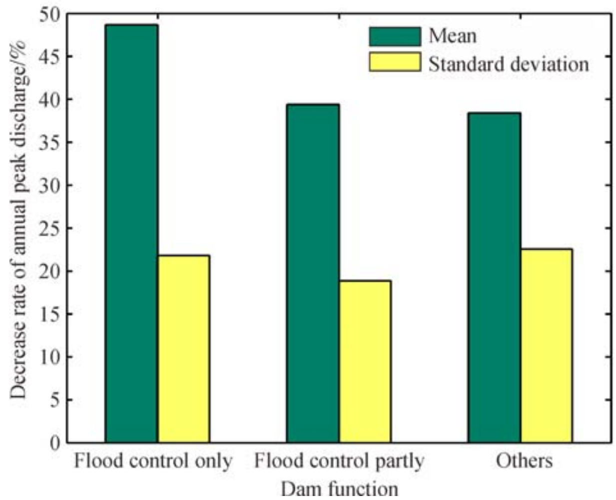

Fig. 5 Relation between changes in the peak discharge series and dam function.

for two dams with the same storage capacity, a dam that is mainly constructed for flood control will have a larger reduction in peak flows, because it does not need to keep water in the reservoir at the beginning of the flooding and thus has greater flexibility to regulate the flood volume. Figure 5 verifies this assertion. In the figure, the green bars represent the effect of dams on the mean values of annual peak discharges, and the yellow bars suggest the impact of dams on the standard deviations. For the 38 U.S. dams, the flood control dams give the greatest flood protection in terms of the mean value. The dams built specifically for flood control, partly for flood control, and for other purposes accounted for 48.67%, 39.38% and 38.38% of the reduction in annual peak discharge, respectively. In addition, compared with the mean, the standard deviation of the annual peak discharge varied less for the different dams. It should be realized that a dam's effect is not only related to its purpose but also to how it is operated. Traditionally, reservoir operations are based on a regulation schedule (Loucks et al., 1981). Those rules are intended to improve reservoir performance by adjusting the release from the reservoir and ultimately changing the downstream flood behavior (Kelman et al., 1990; Barros et al., 2003; Ahmed and Sarma, 2005).

4.2.3 Reservoir capacity/river runoff ratio

Another useful measure for assessing the potential impact of a dam on downstream discharge is reservoir size with respect to mean annual discharge (Graf, 2006). Here, the mean annual discharge was derived from pre-dam annual runoff records to avoid the possible influence of dam regulation on annual flow series. As for the 2 dams without pre-dam yearly runoff records, their mean annual discharges were computed as the average of the post-dam time series. Generally, the degree of the decrease in annual peak discharges caused by a dam is accompanied by an increase in the ratio of reservoir storage capacity (C) to yearly runoff (R), as demonstrated in Fig. 6. The storage capacity of the 38 study dams varies from an equivalent of 0.52% to 2159% of the mean annual runoff. The largest ratio is almost 22 (Bill Williams River (AZ)), which suggests that the reservoir can store a volume equivalent to approximately 22 years' of mean annual runoff. Notably, such a huge amount of storage volume has the potential to considerably decrease the annual maximum discharge and bridge multi-year droughts. On the other hand, the magnitude of floods on the Cowlitz River did not greatly change during the dam regulation period, which can be explained by the relatively small capacity of the Mayfield dam along the river. The Cowlitz River is a basin rich in water resource with 258 m^3/s annual runoff; however, the Mayfield Reservoir only has a small flood storage capacity. Consequently, the reservoir capacity is easily exceeded during the flood season and produces little effect on flood regulation.

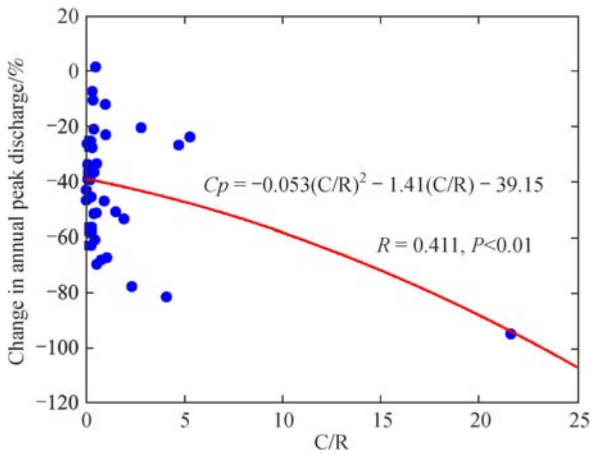

Fig. 6 Relation between changes in the mean annual peak discharge and capacity/runoff ratio.

4.2.4 Reservoir capacity/drainage area ratio

The amount of reservoir capacity (C) of a dam to the area of its drainage (D) can also be used to estimate the impact of a dam on flood characteristics. A scatter plot of the ratios of storage capacity (C) to drainage area (D) against the peak flow change rates for the 38 study sites is shown in Fig. 7. It can be seen from the figure that dams with large C/D ratios always have better peak flood control. On the other hand, dams with small C/D ratios regulate downstream flows less. The Wabash River, which has a 1768 km^2 drainage area with a capacity of 0.67 km^3, had the smallest ratio C/D. By contrast, the Trinity River has

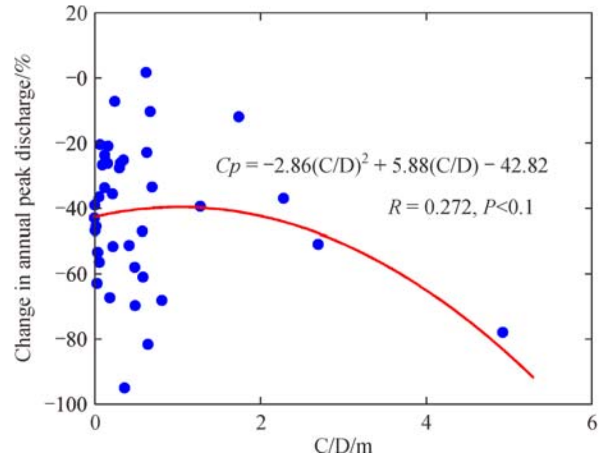

Fig. 7 Relation between changes in the mean annual peak discharge and capacity/drainage-area ratio.

4.93 km^3 of reservoir storage in charge of a smaller area (692 km^2). As a consequence, the Trinity River had twice the flood reduction performance of the Wabash River.

5 Conclusions

Dams are an important component of the American hydrologic system. However, little knowledge is available about how these dams and their reservoirs alter downstream floods on a nationwide scale. The objective of this research is to fill in this gap by comparing the pre- and post-dam flood characteristics. The following conclusions are drawn from this paper:

1) The construction of dams can significantly modify the flood magnitude on a national scope. Different degrees of modification in annual peak discharge were observed for the 38 rivers. Thirty-seven rivers had significant mean decrease rates that varied from 7.4% to 95.14%, with a mean at 43.17%. For 32 out of the 38 river basins, there were observable reductions of the standard deviation from 3.71% to 94.48%.

2) Dam regulation has a significant influence on the probabilistic model of the river peak discharge series. This is mainly reflected in the reduction of high-frequency events and regularizing the peak discharges over a relatively small range.

3) Four driving factors have been determined to explain the effects of dams on the behavior of floods: geographic location of the dam, dam function, the ratio of the storage capacity of the dam to mean annual runoff of the river (C/R), and the amount of reservoir storage to the area of its drainage (C/D). At lower latitudes, such as in the southern United States, dams cause a greater change in annual peak flows due to the large variance of the seasonality of precipitation. Dams that are built exclusively for flood regulation may cut off more flood peaks because they are

specifically intended to store the extra flood discharge. As C/R and C/D increase, the degree of modification in annual maximum discharge grows accordingly.

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Appendix

Table A1 Critical levels (T_{90}, T_{95}, and $T_{97.5}$) of the SNHT test for single shift

n	10	20	30	40	50	60	70	80	90	100	150	250
T_{90}	5.05	6.10	6.65	7.00	7.25	7.40	7.55	7.70	7.80	7.85	8.05	8.35
T_{95}	5.70	6.95	7.65	8.10	8.45	8.65	8.80	8.95	9.05	9.15	9.35	9.70
$T_{97.5}$	6.25	7.80	8.65	9.25	9.65	9.85	10.10	10.20	10.30	10.40	10.80	11.20

Source: Alexandersson and Moberg (1997).