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Scale-independent assessment of discharge reduction and riparian disconnectivity following flow regulation by dams

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ABSTRACT

By using the established hydraulic relationships among flood frequency, flood magnitude, and river-channel capacity, we develop a scale-independent assessment of the hydrogeomorphic impacts of 21 dams across the United States that have broad ranges in function and contributing drainage area. On the basis of generalized extreme value (GEV) analysis of pre- and post-dam hydrologic records, our analysis indicates that the 2 yr discharge has decreased ~60% following impoundment, exceeding the magnitude of climatically triggered discharge reductions occurring during the Holocene. Reductions in the frequency of the pre-dam 2 yr discharge have been equally profound. The pre-dam 2 yr flood has occurred on average twice per site, whereas statistical analysis indicates that it should have occurred ~20 times. Furthermore, floods greater than bankfull have been essentially eliminated by dams, completely disconnecting the riparian zone from riverine influence. Our analyses herein suggest that a critical threshold of disconnectivity exists and corresponds approximately to the pre-dam 5 yr flood. This similar recurrence probability exists independent of region, dam type, or catchment size.

Keywords: dams, hydrologic regime, floods, riparian.

INTRODUCTION

More than 80,000 dams have been constructed in the United States over the past two centuries, with a large pulse of construction occurring between the 1940s and the 1960s, a period when numerous large multipurpose reservoirs of substantial storage were built (Graf, 1999, 2001). These impoundments of all kinds have had major impacts on river hydrology, morphology, and ecology, and these effects have manifested particularly in changes in the timing, magnitude, and frequency of flood events (Benke, 1990; Ligon et al., 1995; Poff et al., 1997; Magilligan and Nislow, 2001). These characteristics of the hydrologic regime largely determine channel morphology and provide the connection between water and sediment discharge and between rivers and their floodplains, key factors ultimately maintaining the diversity and function of these increasingly threatened riparian habitats. However, characterizing the overall extent of dam alterations at large scales, across the wide range of dam types and river systems affected, has proven difficult, in part owing to the array of dam types, varying regional climates, differing initial conditions, and the general lack of robust pre-dam data.

The lack of generalizable information further results because few scale-independent metrics exist to compare impacts from dam to dam. In this study, we develop an approach that uses the most extensive source of pre- and post-dam data—i.e., long-term records of river discharge—to develop a scale-independent assessment of the broad-scale hydrogeomorphic impacts of dams. Stage, the commonly used expression of inundation, is scaled to basin characteristics and thus depends on river size and discharge, watershed drainage area, and valley confinement, which combine to limit site-to-site comparisons. In order to circumvent these scale limitations, we use the pre-dam flow regime, as expressed by the recurrence interval (RI) of the annual flood record, as the appropriate representation of post-dam hydrologic changes. Using the pre-dam recurrence interval as the standardized metric of post-dam changes permits comparison of hydrologic changes across dams, better expresses the disconnectivity of riparian surfaces from flood inundation, and can be used to evaluate changes in both extreme- and moderate-magnitude flows. By utilizing this probabilistic approach, we take advantage of the general, scale-independent hydraulic relationships among flood frequency, flood magnitude, and river-channel capacity. In natural stream channels, ranging in size from small upland streams to large main-stem rivers, the discharge generally necessary to fill the bankfull channel cross section occurs, on average, with a 2 yr recurrence probability (Leopold et al., 1964). Although some variability exists in this relationship, Williams (1978) showed the strong clustering of bankfull discharges and the 2 yr RI flood. The bankfull discharge has also been shown to be the dominant discharge for sediment transport and channel maintenance (Wolman and Miller, 1960; Andrews, 1980; Carling, 1988). Reductions in its occurrence by flow regulation may contribute to channel narrowing, diminished sediment transport, reduced sinuosity, and degraded aquatic ecosystems. The bankfull discharge also sets other geomorphic and ecological thresholds, because floods that exceed this discharge are capable of inundating the adjacent river floodplain. Native riparian biological communities require this flood pulse to keep out competitors, bring in nutrients, create habitat, and enhance seed dispersal, and its elimination contributes to the diminished ecological integrity of floodplains and other riparian surfaces.

METHODS

The National Inventory of Dams (NID) and the U.S. Geological Survey (USGS) Web sites served as the main sources for information on dams, with the latter also providing all the information on the peak

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TABLE 1. SITES USED FOR ANALYSIS

River	Dam(s)	Drainage area (km²)	Dam type	No. of years pre-dam	No. of years post-dam
Bill Williams, Arizona	Alamo	11,999	FC; WS	37	30
Chattahoochee, Georgia	Buford	3030	H; N	54	44
Clinch, Tennessee	Norris	7545	FC; H; N	32	39
Colorado, Arizona	Glen Canyon	289,562	H	42	37
Colorado, Texas	EV Spence	42,367	WS	41	32
Cowlitz, Washington	Mayfield	3626	H	27	38
Coyote, California	Coyote and Anderson	508	WS; H	28	39
Crooked, Pennsylvania	Crooked Creek	720	FC	30	52
Iowa, Iowa	Coralville	8472	FC	55	42
Kaskaskia, Illinois	Carlyle Lake	7042	FC	43	33
Leon, Texas	Belton	9174	FC	30	46
N. Fork Kings, California	Wishon and Courtright	469	H	36	41
N. Santiam, Oregon	Detroit and Big Cliff	1695	FC; I; H	37	48
Olentangy, Ohio	Delaware	1018	FC	35	49
Pound, Virginia	Flannagan	572	FC; WS	38	34
Roanoke, North Carolina	Kerr; Roanoke; Gaston	21,715	FC; H	32	38
S. Fork Flathead, Montana	Hungry Horse	4307	H; FC; I	41	48
Tennessee, Tennessee	Douglas	23,139	H	48	40
Trinity, California	Trinity	1862	H; WS	49	39
Westfield, Massachusetts	Knightville	417	FC	31	54
Wynoochee, Washington	Wynoochee	192	FC; WS	47	27

Note: For dam type: FC–flood control structure; WS–water supply; H–hydropower; I–irrigation; and N–navigation.

flows, both pre-dam and post-dam. In order to acquire a representative and unbiased sample, we searched the NID and USGS databases for gages that are downstream of a dam built during that station's period of record and that have ~30 yr of record both before and after dam construction. Each of the stations was also free from significant diversion or regulation prior to dam construction. These restrictive selection criteria provided 21 gage stations distributed relatively evenly throughout the United States and captured an array of dam types and contributing watershed areas ranging across four orders of magnitude (Table 1). We generated flood frequencies for both pre-dam and post-dam annual peak values by fitting the data to a generalized extreme value (GEV) distribution. The GEV distribution is commonly used to describe hydrologic data involving maxima, such as annual flood peaks. The sample data were fit to the GEV distribution by using L-moments expressed in terms of unbiased probability-weighted moments generated from the sample values (Stedinger et al., 1993). GEV flood-frequency analysis was performed on the pre-dam and post-dam annual flood maxima to determine the magnitude of the pre-dam and post-dam 2 yr discharge and to compare extreme flows across sites. For each site, we further determined the largest post-dam release, and this flow magnitude was subsequently expressed as a flow frequency relative to its pre-dam GEV flood-frequency distribution to determine the magnitude of riparian disconnectivity as expressed in a scale-independent manner. Furthermore, we determined how often the pre-dam 2 yr flood occurred at each site following impoundment to characterize the shifts in the frequency of the pre-dam channel-maintaining flow.

The NID also provided the characteristics of each dam (dam height, length, maximum storage capacity, and latitude and longitude). We located the closest National Oceanic and Atmospheric Administration (NOAA) station with long-standing climate data to determine the mean annual temperature and mean annual precipitation at each site. To establish the variability through the year, we calculated the standard deviation at each site by using mean monthly data for both temperature and precipitation. These climatic and site data were ultimately input into a forward stepwise regression model to determine which set of variables best explained the reduction of the 2 yr discharge following impoundment.

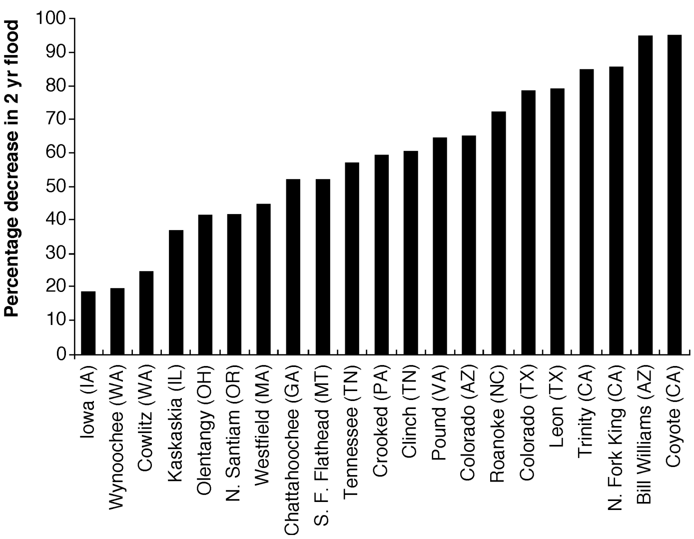

Figure 1. Percent decrease in the magnitude of the 2 yr discharge following impoundment for the 21 rivers studied. Mean decline is 59%. IA–Iowa; WA–Washington; IL–Illinois; OH–Ohio; OR–Oregon; MA–Massachusetts; GA–Georgia; MT–Montana; TN–Tennessee; PA–Pennsylvania; VA–Virginia; AZ–Arizona; NC–North Carolina; TX–Texas; CA–California.

RESULTS

Effects on Bankfull Flows

Major adjustments in the hydrologic regime have occurred following impoundment, including significant changes in both extreme peak discharges and more moderate floods. The 2 yr discharge, which is primarily responsible for channel maintenance, has declined, on average, ~59% following impoundment; four of the sites show a >85% reduction in the magnitude of the pre-dam 2 yr flow (Fig. 1). The smallest reduction of 20% occurred for the Iowa River at Coralville, Iowa, and the other two streams with less than 30% reduction occurred in Washington.

Although three of the four sites exhibiting the largest decline in the bankfull discharge are in California, the effect is not merely a large versus small dam or East Coast versus West Coast phenomenon. Some of the smallest reductions in the 2 yr flood occurred in Western streams of both large (Cowlitz River, Washington: 3626 km^2) and small (Wynoochee River, Washington: 192 km^2) contributing watershed size (Fig. 1), and one of the largest reductions in the 2 yr flood occurred for the Roanoke River, North Carolina, in the humid continental climate of the southeastern United States (72% decrease). Location, however, does matter, and the best combination of variables in the stepwise regression model that can explain the magnitude of decline is latitude and longitude (% decline in 2 yr discharge = 154.5 + (−3.82 × latitude) +

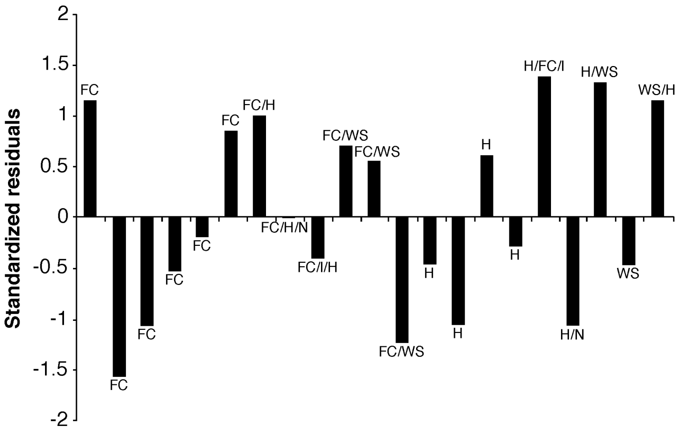

Figure 2. Standardized residuals of the relationship between percent decline in the magnitude of 2 yr flood and both latitude and longitude plotted against dam function. Notation for dam function: FC–flood control structure; WS–water supply; H–hydropower; I–irrigation; N–navigation.

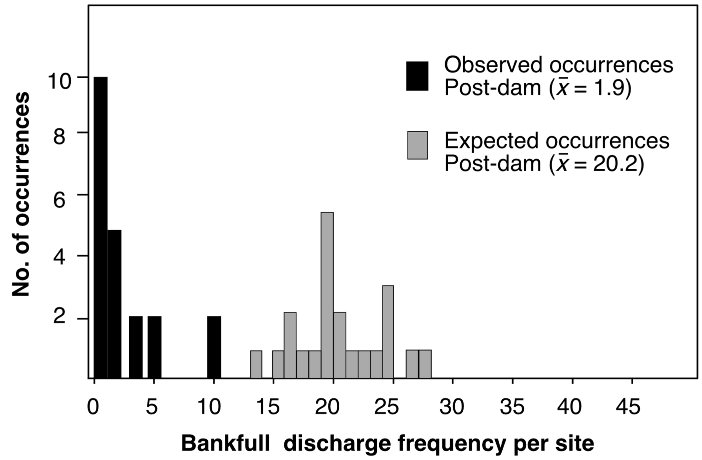

Figure 3. Histogram of observed vs. expected occurrences of 2 yr discharges following impoundment. Expected occurrence is based on 50% probability that the 2 yr discharge will occur in any given year.

(0.53 × longitude); R^2 = .58; p < .01). The locational relationship suggests that dams in southern United States locations with a large variance in the seasonality of precipitation will generate the largest decline in the 2 yr flood. When the standardized residuals of the prediction model explaining the decline in the 2 yr flood by both latitude and longitude are compared to dam characteristics, no significant trends emerge. Dams that are singularly flood-control structures seem to have the most extreme effects, however, but this may generate either high positive or high negative standardized residuals (Fig. 2). The remaining unexplained variance probably relates to particular dam operation rules as they may significantly over-imprint dam location and dam characteristics in predicting reductions in the 2 yr flood.

Post-dam discharge reductions further indicate that the discharge corresponding to the pre-impoundment 2 yr flood has occurred, on average, only 1.9 times per site for all sampled dams. On the basis of statistical expectation, this event should have occurred ~20 times per site on average following impoundment (Fig. 3). For half the sampled rivers, the pre-dam 2 yr flood has never occurred in the post-dam record, indicating that water never reaches, or exceeds, the level of the pre-dam floodplain surface.

Effects on Extreme Flows

Adjustments in high overbank flows have been equally dramatic. For the majority of dammed rivers, the largest post-impoundment release over a 40–60 yr record merely corresponds, on average, to the pre-dam 2 yr flood (Fig. 4). The largest post-dam releases in 18 of the 21 sampled sites were below the pre-dam 5 yr recurrence interval event, indicating that all riparian surfaces above this flow level have been completely disconnected from the modern, post-dam hydrologic regime (Fig. 4). Two major outliers exist. The Coralville Dam on the Iowa River almost failed during the 1993 Midwest floods, and the large release resulted from the extensive spilling to save the dam. The largest outlier for maximum flow release is the Mayfield Dam on the Cowlitz River in Washington. The Mayfield Dam is a single-function hydropower facility with minimal annual range in reservoir elevation (1–2 m), and it is immediately downstream from a significantly larger hydropower facility. Large releases are usually necessary from Mayfield Dam to provide storage for the large peaking releases from the immediately upstream Mossyrock Dam.

Despite these two major outliers, the results for the remaining sites indicate the significant magnitude of riparian disconnectivity following impoundment. Although previous case studies have identified that flow regulation leads to riparian disconnectivity (Stanford and Ward, 1993; Nislow et al., 2002), our approach expresses this disconnectivity more universally and identifies its threshold recurrence interval level of ~5 yr. This similar recurrence probability of disconnectivity exists independent of region, dam type, or catchment size.

Ecological and Geomorphic Implications

Numerous channel properties are controlled by the 2 yr discharge, and the 60% average reduction in its magnitude and the lack of occurrence of the pre-dam 2 yr discharge for half the sites indicate that significant channel adjustments should occur. Fluvial theory suggests that stream channel cross-sectional area, slope, and sediment transport should all be reduced significantly following a reduction in the bankfull discharge as shown herein. These theorized adjustments have been frequently observed, with reductions in stream channel cross-sectional morphology, changes in channel planform and/or bed elevation, and enhanced bed sedimentation commonly occurring following impoundment (Petts and Pratt, 1983; Williams and Wolman, 1984; Andrews, 1986; Hadley and Emmett, 1998; Brandt, 2000).

The lack of overbank inundation completely limits the transport of sediment, nutrients, or water onto higher floodplain surfaces. Riparian and river-terrace communities harbor unique species and perform critical ecosystem functions, and these results indicate that hy-

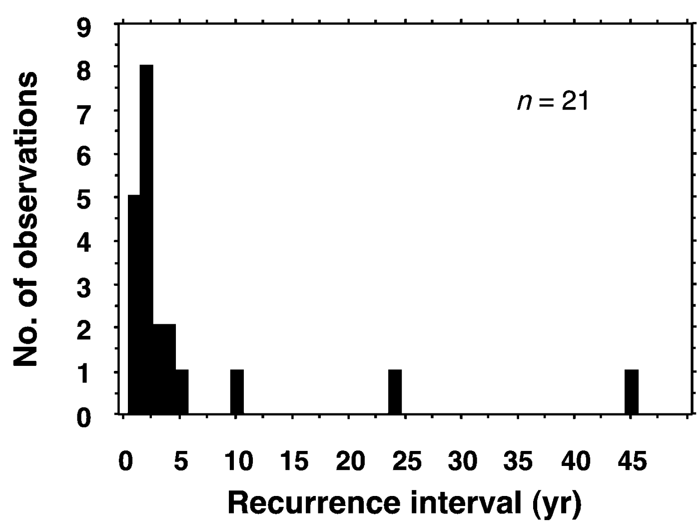

Figure 4. Histogram of recurrence interval of largest post-dam release. Recurrence interval of this largest flow is expressed relative to pre-dam flood-frequency analysis for each site.

drologic alteration is currently threatening long-term ecosystem stability and biodiversity nationally. At best, lower riparian surfaces (those within the pre-dam 5 yr floodplain) may be inundated following impoundment, but most floodplains downstream of dams above the pre-dam 5 yr flood level have not been inundated, indicating that these are now hydrologically and ecologically relict surfaces.

The diminished occurrence of moderate-magnitude floods will directly affect both riparian and in-channel community structure. Dams are likely to have strong, but complex, effects on substratum composition, an important determinant of in-stream algal, benthic invertebrate, and fish community structure (Power et al., 1996). Because of the reduced sediment loads downstream of the dam, channel armoring may be enhanced, or the reduced flows may lead to embeddedness if the tributaries contribute more sediment than the main-stem has the capacity to transport (Andrews, 1986). Where threatened habitats and species frequently exist on low-lying islands formed and maintained by river-transported sediments, this effect may be significant. In addition to effects on substratum composition, previous studies indicate that predictable disturbance of the substratum associated with bankfull floods is critical for the maintenance of species diversity and food-web structure (Wootton et al., 1996).

Comparison to Climate-Change Hydrogeomorphic Influences

These results for both high and moderate flows portray the significant effects of impoundment on channel and riparian systems. Anthropogenic disturbances can have profound influences on hydrologic regimes, and dams may have greater effects on watershed hydrology than other anthropogenic disturbances, including logging or urbanization, and may greatly outweigh the range of naturally induced climatic changes. For example, by using channel dimensions preserved in relict oxbows, Knox (1985) demonstrated that bankfull discharges differed by approximately ±30% in Wisconsin stream systems over the range of Holocene climatic changes. Even during the mid-Holocene drought, the driest postglacial climatic episode, bankfull discharges were reduced only 30% compared to the modern hydrologic regime (Knox, 1985). Yet, the modern impacts of dams, as revealed herein, can reduce 2 yr discharges by as much as 95%. Even the average 60% reduction (Fig. 1) exceeds the Holocene-scale bankfull channel reductions that have been characterized either in terms of measured (Knox, 1985) or modeled reductions (Arora and Boer, 2001).

The reduction in peak flood magnitude by dams corresponds to the magnitude of maximum stage reductions documented for Holocene climatic shifts where maximum flood depths during extreme dry periods may just exceed the bankfull channel (Knox, 1993). Our results for anthropogenically generated effects similarly show that these reduced discharges and stage reductions occur; however, the effects may exceed climatically triggered stage reductions. Half the sites in our sample have never had peak flow stages above the pre-dam bankfull channel margins following impoundment.

CONCLUSIONS

Overall our approach provides a quantified assessment using readily available data of the broad extent of hydrogeomorphic alteration by dams and indicates the hydrologically profound dimension of the riparian effects of impoundment. Given the fact that the great majority of rivers in the United States are currently affected by dam impoundment (Benke, 1990; Graf, 1999) and that hydrogeomorphology is tightly linked to river ecosystems, our results point to the extensive and pervasive effects of impoundment. Impoundment significantly affects the magnitude and frequency of both moderate and extreme flows, and these effects manifest across a wide range of dam types and geographic settings. The magnitude of hydrologic changes shown by our analysis indicates that a similarly profound ecological shift should result, as the greater the deviation in flow regime from predisturbance conditions, the greater should be the expected ecological response (Poff, 2002).

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