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Changes in hydrologic regime by dams

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Abstract

Dams have major impacts on river hydrology, primarily through changes in the timing, magnitude, and frequency of low and high flows, ultimately producing a hydrologic regime differing significantly from the pre-impoundment natural flow regime. This paper presents the analysis of pre- and post-dam hydrologic changes from dams that cover the spectrum of hydrologic and climatic regimes across the United States. Our overall goals are to document the type, magnitude, and direction of hydrologic shifts because of impoundment. Using the entire database for the National Inventory of Dams (NID) for dams possessing longstanding U.S. Geological Survey (USGS) gages downstream, we identified 21 gage stations that met length-of-record criteria encompassing an array of types of dams and spanning four orders of magnitude in contributing watershed area. To assess hydrologic changes associated with dams, we applied a hydrologic model, the Indicators of Hydrologic Alteration (IHA), supplemented with orientation statistics for certain hydrograph parameters. Dams had significant impacts on the entire range of hydrologic characteristics measured by IHA. For many characteristics, the direction and significance of effects were highly consistent across the 21 sites. The most significant changes across these sites occurred in minimum and maximum flows over different durations. For low flows, the 1-day through 90-day minimum flows increased significantly following impoundment. The 1-day through 7-day maximum flows decreased significantly across the sites. At monthly scales, mean flows in April and May tend to decline while mean flows in August and September increase. Other significant adjustments included changes in annual hydrograph conditions, primarily in the number of hydrograph reversals that has generally increased for almost all sites following impoundment. The number of high pulses has increased following impoundment but the average length declines. The mean rate of hydrograph rise and fall has declined significantly. These results indicate that the major pulse of dam construction during the previous century has modified hydrologic regimes on a nationwide scale, for large and small rivers.

Keywords: Dams; Riparian; Hydrologic regime; Floods; Low flow

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1. Introduction

Although large dams provide numerous socio-economic benefits, considerable recent re-evaluation has occurred because of their associated ecological

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costs with many NGOs and other environmental agencies clamoring for their removal. This effort has led to the removal of over 500 dams nationwide, with many presently slotted for deconstruction although these are primarily small-head, run-of-the river facilities (Doyle et al., 2003). This concern about the ecological integrity of rivers because of impoundment results because dams profoundly affect river hydrology, primarily through changes in the timing, magnitude, and frequency of high and low flows (Benke, 1990; Ligon et al., 1995; Power et al., 1996; Graf, 1999, 2001; Magilligan and Nislow, 2001; Nislow et al., 2002), ultimately producing a hydrologic regime differing significantly from the pre-impoundment natural flow regime (Poff et al., 1997). The hydrologic regime of a watershed determines an array of geomorphic processes and properties and provides the link between rivers and the riparian zone, ultimately maintaining the diversity and function of these increasingly threatened habitats (Stanford and Ward, 1993). In some rivers, elimination of floods following impoundment has extirpated native riparian forest communities, subsequently reducing biodiversity (Molles et al., 1998; Nislow et al., 2002) and causing major changes in river food webs (Wootton et al., 1996). Although popular with certain stakeholders, removal of dams has received less recent public and political support, while management strategies of flow regulation have emerged as more viable options for channel and riparian restoration. Regardless of which option, flow regulation or removal of dams, is used to restore ecological integrity; the actual scientific outcome (i.e. maintaining or generating ecological integrity) remains essentially enigmatic.

Generalizing the hydrogeomorphic effects of impoundment has remained elusive because of the array of types of dams, differing regional climates and initial conditions, and minimal pre-dam data. Although considerable recent research exists concerning the hydroecological impacts of dams, most are single case studies and few syntheses exist that analyze the spectrum of geomorphic adjustments across regions, climatic zones, or dam types. Most studies on the geomorphic impacts chronicle changes in stream channel cross-sectional morphology over time (Petts and Pratts, 1983; Hadley and Emmett, 1998); changes in channel planform or bed elevation downstream of reservoirs (Chien, 1985; Brandt, 2000); or sedimentological changes downstream of a dam (Graf, 1980; Petts, 1984; Chien, 1985; Andrews, 1986; ASCE, 1992; Schmidt et al., 1995; Elliott and Parker, 1997; Pitlick and van Steeter, 1998; Phillips, 2001). These geomorphic adjustments commonly contribute to the diminished ecological integrity of streams and greater riparian systems. The ecological effects may be directly linked to the hydrologic changes (e.g. enhanced low flows) or indirectly through the mediating influence of geomorphic changes in the fluvial system (e.g. embeddedness).

The hydrologic changes associated with the regulation of flow are reflected in the shape and characteristics of the hydrograph and/or flow duration curve, which often correspond to specific ecological responses. Typically, the dominant impact is diminished large flows, which can significantly disrupt aquatic life cycles (Bain et al., 1988; Kingsolving and Bain, 1993; Scheidegger and Bain, 1995) and contribute to adjustments in riparian community structure ultimately promoting dominance of invasive exotics (Johnson, 1994; Nilsson, 1982; Nislow et al., 2002). But adjustments to high flows are not the exclusive cause of diminished ecological integrity. Other components of the hydrograph and flow duration curve also have corresponding ecological responses, especially those associated with changes in the timing and duration of flows and in the rates of change and frequency of hydrograph rises and falls (Richter et al., 1996; Poff et al., 1997; Hadley and Emmett, 1998; Puckridge et al., 1998; Dugger et al., 2002). For example, sudden increases in bar saturation by rapid flow releases during hydropower production enhance bar erosion through abrupt changes in pore water pressure leading to sapping. These ramping effects contribute to riparian habitat loss and unsuccessful recruitment of tree seedlings (Cushman, 1985; Rood and Mahoney, 1990). These rapid stage changes may further strand vulnerable populations and enhance predation. Furthermore, numerous ecological functions, including spawning and migration cues, depend upon some modicum of timing predictability (Næsie et al., 1995; Montgomery et al., 1983); and changes in the timing of low and high flows following impoundment may be as dramatic as the changes in the magnitude of these flows.

In order to combat some of these hydrological impacts on riparian ecology, recent attention focuses on strategies of flow management that best mimic pre-impoundment conditions. Rather than concentrating primarily on a single index species, these new strategies, instead, attempt to provide sustainable flows that best serve the diverse array of aquatic organisms and riparian habitats. The re-introduction of high flows into the post-dam hydrologic regime through controlled releases, as conducted in the Grand Canyon in 1996, figure prominently into management decisions; yet these prescriptive approaches to maintain and restore specific riparian habitat are not unproblematic (Powell, 2002). The timing and magnitude of these controlled releases are critical for specific habitat (cf. Wu, 2000; Schmidt et al., 2001), yet no single flow or discharge will universally ameliorate or mitigate existing disturbed environmental conditions (Kondolf and Wilcock, 1996). The establishment and orchestration of these controlled, flushing flows are part of larger "adaptive management" strategies advocated by management agencies, whereby riparian and watershed stakeholders engage in a "trial and error" approach of flow releases and subsequent target evaluation (Lee, 1999).

The search for reference conditions has broad geomorphic and management applications. The ecological and hydrogeomorphic responses to dams have been well documented, yet little is known about the pre-impact boundary reference conditions. In many instances, the reference natural flow may be the ultimate target or goal of management options, but the actual composition of the pre-dam hydrologic regime is unknown. In this paper, we present the analysis of pre- and post-dam hydrologic changes from dams that cover the spectrum of hydrologic regimes across the United States. Our overall goals are to document the type, magnitude, and direction of hydrologic shifts because of impoundment. We apply a hydrologic model, the Indicators of Hydrologic Alteration (Richter et al., 1996), to an array of dams ranging in watershed contributing drainage across four orders of magnitude. The types of dams include hydropower, flood control, water supply facilities, or some combination of all three types. The fundamental research questions for this analysis were to evaluate for each hydrologic parameter in the model: (i) did the majority of stations experience significant post-dam changes; (ii) were these changes consistent in magnitude and direction; and (iii) were the changes associated with differences in geography, climate, and/or type of dam?

2. Methods

2.1. Data sources

To generate a representative and unbiased sample, we searched the entire database of the National Inventory of Dams (NID) for dams possessing long-standing U.S. Geological Survey (USGS) gages downstream of the dam, with ~30 years of daily and peak flow data before and after dam construction. We further required that each of the stations be free from significant diversion or regulation prior to dam construction.

2.2. Changes in hydrologic regime

To ascertain the hydrologic shifts associated with impoundment, we utilized a model, the Indicators of Hydrologic Alteration (IHA), developed by The Nature Conservancy (Richter et al., 1996). This model uses daily discharges and calculates 32 indices that describe the hydrologic regime for that station (Table 1). The 32 indices generated by IHA consist of five major categories: (i) magnitude; (ii) magnitude and duration of annual extreme conditions; (iii) timing of annual extreme conditions; (iv) frequency and duration of high and low pulses; and (v) rate and frequency of changes in conditions. The 32 hydrologic characteristics were developed by Richter et al. (1996) because of the close association with ecological functioning, either in terms of population dynamics (e.g. spawning cues), predator–prey relationships, or species competition. Not all indices may be affected by impoundment at a specific gage or in a particular region, but the model was developed to be inclusive of most types of hydrologic disturbances that correspond to potential ecological impacts.

Using daily discharge data, IHA evaluates the magnitude and changes in minima and maxima, synthesizes and groups these two extremes over several temporal scales (1 day, 3 days, 7 days, 30 days, and 90 days), and determines mean monthly streamflow (Table 1). The Julian date of the annual maxima and minima are determined. The method does

Table 1
Output parameters for the IHA model (the 32 output parameters are grouped into five major categories; see Richter et al., 1996)

IHA statistics	Regime characteristics	Hydrologic parameters
Group 1: Magnitude of monthly water conditions	Magnitude Timing	Mean value for each calendar month
Group 2: Magnitude and duration of annual extreme water conditions	Magnitude Duration	Annual minima 1-day means
		Annual maxima 1-day means
		Annual minima 3-day means
		Annual maxima 3-day means
		Annual maxima 7-day means
		Annual minima 7-day means
		Annual maxima 30-day means
		Annual maxima 30-day means
		Annual minima 90-day means
		Annual maxima 90-day means
Group 3: Timing of annual extreme water conditions	Timing	Julian date of each annual 1-day maximum
		Julian date of each annual 1-day minimum
Group 4: Frequency and duration of high and low pulses	Magnitude Frequency Duration	No. of high pulses each year
		No. of low pulses each year
		Mean duration of high pulses within each year
		Mean duration of low pulses within each year
Group 5: Rate and frequency of water condition change	Frequency Rate of change	Means of all positive differences between consecutive daily means
		Means of all negative differences between consecutive daily values
		Number of rises
		Number of falls

not characterize the storm hydrograph per se, but the more dynamic elements of hydrologic response are based on comparison of mean daily discharges, conditions expressed by the annual hydrograph. In this manner, the model calculates the daily rise rate (analogous to a ramping rate for post-dam conditions) and fall rate, and determines the mean annual rise and fall rates. A sequence, or run, of continuously rising (or falling) mean daily discharges equals a rise (or fall), and the number or rises (or falls) is determined for each year (Fig. 1). If a mean daily discharge differs in direction (rise vs. a fall), it counts as one reversal, which are then summed for the year. Often times, the frequency and duration of high and low flows become critical ecological characteristics (Benke, 1990; Townsend and Foster, 2002), and IHA characterizes the tails of the distribution by determining the pulsing nature of hydrologic variation. A pulse is a hydrologic period where discharges (or sequences of daily discharges) exceed the 75th percentile, or falls below the 25th percentile, of the pre-dam ranked daily discharges. Pulses are essentially representing the tails (75th and 25th percentiles) of the pre-dam flow duration curve. The number of high and low pulses and the mean duration are calculated for each year. We determined all 32 variables for each of the 21 gages.

Besides changing the shape of the hydrograph, impoundment can have profound effects on the timing of minimum and maximum flows (Næsie et al., 1995). Analyzing the effects of impoundment on the timing of 1-day extremes (maxima and minima) requires further transformation of the pre-dam and post-dam data. Temporal data of this kind are very similar to orientation data for spatial statistics. Because time is continuous, determining the mean date of minimum and maximum flows requires transforming the Julian date (Θ) by vector statistics (Gumbel, 1954; Magilligan and Graber, 1996). Orientation statistics utilize a circular histogram (also known as a rose diagram) to express the temporal continuity of data from one year to the next. This technique characterizes continuous flow data where, for example, January 5th is closer to December 25th than it is to March 5th. The Julian date (i) of either the 1-day minimum or maximum flow can be converted to a circular histogram by converting it to a 360° range:

$$\Theta = 360^{*}(i/365). \tag{1}$$

For each site, the vector mean date for minimum and maximum flows was determined for the pre-dam and post-dam conditions using the standard equation (Eq. (2)) for vector mean statistics for orientation data (Mardia, 1972; Davis, 1986; Magilligan and Graber, 1996).

$$\text{Vector Mean} = X_{\mathrm{o}} = \arctan\left(\sum_{i=1}^{n}\sin\Theta \Big/ \sum_{i=1}^{n}\cos\Theta\right). \tag{2}$$

2.3. Analysis

For each of the 32 variables, we calculated the mean and standard deviation for the pre- and post-

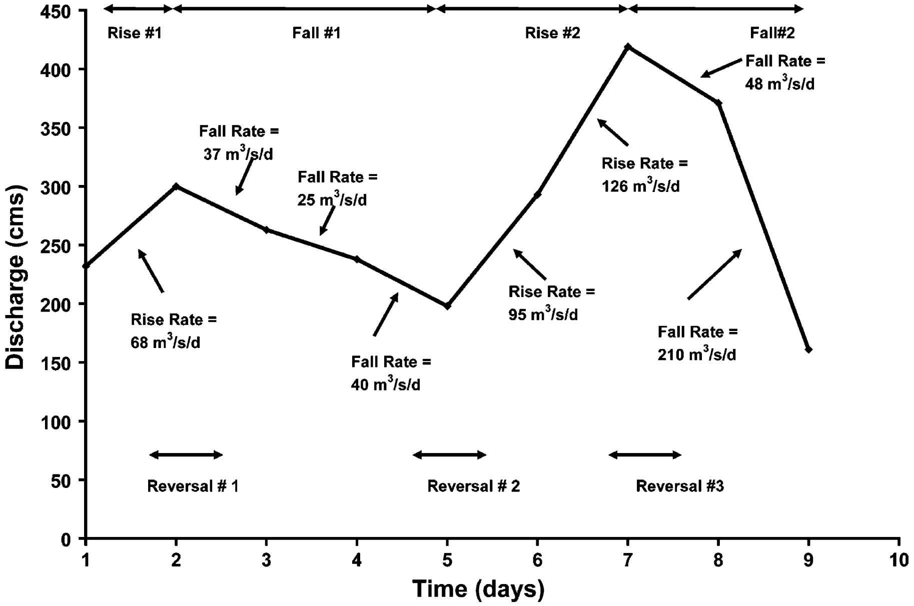

Fig. 1. IHA parameters for characteristics of the annual hydrograph.

dam hydrologic periods with, on average, 37 and 39 years of data, respectively. These two periods were then compared statistically using a Student's *t*-test to determine if the means were statistically significant. To determine which sets of variables controlled the type and direction of hydrologic response to dams, we used two different statistical approaches. First, we used a stepwise regression model that incorporated attributes of dams (size, reservoir storage capacity, latitude, and longitude) and climatic region. Climatic characteristics also control the hydrologic regime and, thus, the response to impoundment. For each station, we located the closest weather station and determined the mean precipitation and temperature. The degree of seasonality is expressed for each station as the standard deviation in monthly precipitation and temperature. Second, we used discriminant analysis to test whether the hydrologic response variables could statistically discriminate amongst primary types of dams (flood control vs. hydropower) and geographical regions. To define geographic locations, we used k-means cluster analysis to define three groups (maximum number of groups while maintaining sufficient sample sizes per group) based on latitude and longitude.

3. Results

Selection criteria provided 21 gage stations distributed relatively evenly throughout the United States (Fig. 2), although the Upper Plains states are poorly represented. These dams range in contributing watershed size across four orders of magnitude and represent an array of types of dams (Table 2). The effects of impoundment cut across the array of hydrologic indices captured by IHA. The first part of the analysis will cover the actual hydrologic shifts that have occurred because of impoundment, and the second part will address the patterns of response as a function of climate, type of dam or function, and geographic location.

3.1. Magnitude of the extremes

Dams are quite effective at accomplishing what they were designed to do as the most dramatic shifts occur in the decreased magnitude of 1-day maximum flows. On average, 1-day maximum flows have declined ~55%, with 20 of the 21 sites experiencing a statistically significant decline in peak flows (Table 3). Only one site, the Wynoochee River in Washington, experienced an increase in 1-day maximum flows, but this was not

Fig. 2. Location of sites used for analysis.

statistically significant. The decreased flows ranged from a low of 21% for the single-function, hydropower Mayfield Dam on the Cowlitz River to a high of a 79% reduction in the magnitude of the 1-day maximum flow for the Colorado River in Texas.

As the flow duration window expands for maximum flows, the effect of impoundment diminishes significantly, especially for flows on monthly to seasonal scales (i.e. 30-day to 90-day maximum flows) (Table 3). For the 1-day through 7-day flow durations, more than half the sites experienced a statistically significant decline, with at least a 39% average decline occurring even at the timescale of the week. Although several sites still manifest significant declines at the monthly or seasonal durations, more than half the sites experienced no significant effects at flows of longer duration.

A somewhat different pattern emerges for minimum flows. On the whole, minimum flows tend to increase following impoundment, but this is most true for the longer duration events (Table 4). One-day minimum flows generally increase, but this was only significant for 10 of the 15 significant pre- vs. post-dam differences. For those sites experiencing increased 1-day minimum flows, the average increase was 124%, while sites where 1-day minimum flows decreased showed a 44% average decline (Table 4). In contrast to maximum flows that showed less significant effects as the flow duration window increased, minimum flows showed significant and progressively consistent trends with increasing flow durations. Fourteen of the twenty-one sites exhibited significant post-dam effects even at the 90-day flow duration. The most consistent relationship occurred at the monthly timescale where 16 of the 21 sites had a significant flow increase averaging 86% (Table 4).

3.2. Changes in hydrograph variability

Equally profound effects have occurred in parameters associated with the shape of the hydrograph. The characteristics of the hydrograph, as revealed by IHA, show significant changes in the number of reversals and in mean rise rates and fall rates. IHA does not capture the diel variation as it is based on mean daily

Table 2
Sites used for analysis and their associated characteristics

River (State)	Dam(s)	Drainage area (km^2)	Type of dam[a]
Bill Williams (AZ)	Alamo	11,999	FC/WS
Chattahoochee (GA)	Buford	3030	H/N
Clinch (TN)	Norris	7545	FC/H/N
Colorado (AZ)	Glen Canyon	289,562	H
Colorado (TX)	EV Spence	42,637	WS
Cowlitz (WA)	Mayfield	3626	H
Coyote (CA)	Coyote and Anderson	508	WS/H
Crooked (PA)	Crooked Creek	720	FC
Iowa (IA)	Coralville	8472	FC
Kaskaskia (IL)	Carlyle Lake	7042	FC
Leon (TX)	Belton	9174	FC
N. Fork King (CA)	Wishon and Courtright	469	H
N. Santiam (OR)	Detroit and Big Cliff	1695	FC/I/H
Olentangy (OH)	Delaware	1018	FC
Pound (VA)	Flannagan	572	FC/WS
Roanoke (NC)	Kerr; Roanoke; Gaston	21,715	FC/H
S. Fork Flathead (MT)	Hungry Horse	4307	H/FC/I
Tennessee (TN)	Douglas	23,139	H
Trinity River (CA)	Trinity	1862	H/WS
Westfield (MA)	Knightville	417	FC
Wynoochee (WA)	Wynoochee	192	FC/WS

[a] FC denotes flood control structure; WS denotes water supply; H denotes hydropower; I denotes irrigation; and N denotes navigation.

discharge, yet even at the scale of day-to-day variation, major hydrograph changes have occurred from impoundment.

Statistically significant changes occurred in the number of hydrograph reversals in 17 of the 21 sites following impoundment (Table 5), with reversals increasing in 13 sites and decreasing in 4 sites. For those sites significantly increasing the number of reversals, the mean increase was 55%, while the average change for sites having a significant decrease was 17%. Besides greatly modifying the sequencing of hydrograph peaks, the day-to-day rate of change was also dramatically affected, especially for the rise rate (i.e. the climbing limb of the hydrograph). Only the Iowa River at Coralville, Iowa lacked a significant change in this parameter. Of the 20 significant relationships, almost all of the sites experienced a decreased rise rate following impoundment (Table 5). For those 18 sites experiencing declining rise rates, the daily discharge rate on the hydrograph rising limb decreased 48% on average. For fall rates, a less consistent pattern emerged as only 13 sites had significant changes and the direction of change was not consistent (Table 5). For most of the sites with significant post-impoundment effects, fall rates, like the pattern for rise rates, have tended to decline with a 40% average reduction occurring.

The pulsing response of flows serves critical riparian functions. Changes in the frequency and duration of flows of a particular stage and discharge can significantly disrupt terrestrial and aquatic ecology (Benke, 1990; Townsend and Foster, 2002). The greatest effect for these 21 sites occurred in the number of post-dam high and low pulses, especially for the high pulse number where 16 of the sites experienced a statistically significant change (Table 6). Of these 16 significant sites, 9 of them increased the number of high pulses while 7 decreased the number of high pulses, making any generalizations difficult. The percent change in the number of days of increased low pulses and high pulses was 141% and 116%, respectively (Table 6). For length of flow, only half the sites manifested significant changes either in terms of low pulse length or high pulse length, yet these effects were more consistently in the direction of reduced lengths for both parameters (Table 6). For high flows, although the number of high pulses above the pre-dam 75th percentile has increased, the average duration (in days) has tended to decrease.

3.3. Changes in the timing of flows

Whether these dams are flood control, irrigation, or hydropower, they are all associated with storing water for subsequent releases. This storing component significantly affects the release timing and greatly disrupts the pre-impact natural flow regime’s expected timing of flows. This effect occurs on the scale of total monthly streamflow and in the timing of extreme maximum and minimum flows. The greatest effect of impoundment at monthly scales is concentrated in two dominant seasons: August–October and April–May (Table 7). For the late summer and early fall season, this is usually the time of generally sustained low flows throughout the US that are now augmented by flow releases from dams. Flows in April and May are

Table 3
Percent difference in the means between pre-impact and post-impact conditions for maximum flows for different flow durations[a]

	1-day max Q	3-day max Q	7-day max Q	30-day max Q	90-day max Q
Bill Williams River	−73**	−58*	−35	−1	14
Chattahoochee River	−64**	−53**	−38**	−6	−6
Clinch River	−67**	−63**	−51**	−20**	16
Colorado River (AZ)	−64**	−64**	−64**	−61**	−55**
Colorado River (TX)	−79**	−83**	−83**	−80**	−79**
Cowlitz River	−21*	−17	−7	2	5
Coyote Creek	−79**	−76**	−72**	−60**	−54**
Crooked Creek	−38**	−33**	−17*	−4	3
Iowa River	−26*	−21*	−11	25	42**
Kaskaskia River	−44**	−42**	−34**	−2	14
Leon River	−72**	−62**	−50**	−17	−4
NF King River	−75**	−76**	−80**	−84**	−86**
North Santiam River	−43**	−37**	−20**	−3	−6
Olentangy River	−36**	−21*	−1	−4	−10
Pound River	−52**	−26**	−17	−17*	−13
Roanoke River	−71**	−66**	−54**	−21**	−11
SF Flathead River	−49**	−48**	−46**	−41**	−34**
Tennessee River	−57**	−51**	−37**	−24**	−17**
Trinity River	−51**	−71**	−61**	−60**	−70**
Westfield River	−34**	−16	−1	2	2
Wynoochee River	16	−2	8	1	3
Mean	−51	−47	−37	−23	−16
Mean increase	16	N/A	8	7	12
Mean decrease	−55	−47	−39	−30	−34

[a] If a significant difference exists between the two periods at the 5% level, it is designated with *; if a significant difference exists between the two periods at the 1% level, it is designated with **.

generally reduced to allow reservoir storage either for flood control or for later hydropower generation. For some sites, especially in the southwestern and western US, summer flows tend to increase, but this was not true of all sites.

Trends evident at the coarse scale of the mean monthly condition become progressively more pronounced at the finer scale of the 1-day extremes for minima and maxima. The mean Julian date for the 1-day minimum and maximum flows were determined using orientation statistics (Eq. (2)) that capture the circular and continuous nature of temporal data. This effect can be seen, for example, in the data for the Colorado and Chattahoochee Rivers. Because of the predominant snowmelt runoff regime typical of streams draining the Rockies, the Colorado River pre-dam maximum flows were highly concentrated within a very tight cluster of dates, ranging from May 15 to June 30 with a mean of May 31 (Fig. 3). Following impoundment, the release strategies from the Glen Canyon Dam dictate the timing of the 1-day maximum flow. Based upon an array of climatic, ecological, and engineering decisions, the date has become progressively more variable and unpredictable in the post-dam environment. The mean date has shifted 34 days to July 3, but the variance has changed even more dramatically (Fig. 3). For 1-day minimum flows, the pre-impact date was somewhat bi-modal for the Colorado River, but has become more multi-modal following impoundment resulting in a 69-day shift in the expected timing of its occurrence and in a greater variance. For large rivers in the humid southeastern US, a somewhat different pattern emerges. The Chattahoochee River had a tight temporal clustering of the 1-day minimum flow pre-dam, with an expected date of September 26. Impoundment has shifted that mean date from early fall to late summer (August 26) and also profoundly changed its variance (Fig. 4). For high flows, the mean date has shifted almost 2 months from February 19th to April 11, and management strategies have also made it less temporally predictable.

These two examples from contrasting regions reveal the major changes in the expected date of the

Table 4
Percent difference in the means between pre-impact and post-impact conditions for minimum flows for different flow durations[a]

	1-day min Q	3-day min Q	7-day min Q	30-day min Q	90-day min Q
Bill Williams River	19	29	39	156*	181
Chattahoochee River	−4	18*	38**	42**	26**
Clinch River	−87**	−73**	−48**	39*	61**
Colorado River (AZ)	31*	61**	71**	57**	24*
Colorado River (TX)	156	166	165	33	−47**
Cowlitz River	81**	84**	85**	74**	49**
Coyote Creek	0	14	47	134*	175**
Crooked Creek	133**	132**	119**	62*	18
Iowa River	48*	37	36	45*	88**
Kaskaskia River	−19	−11	−3	12	88*
Leon River	−73*	−64	−55	−14	−33
NF King River	199**	192**	177**	141**	26
North Santiam River	79**	80**	79**	69**	62**
Olentangy River	212**	226**	187**	103**	74**
Pound River	570**	635**	629**	434**	192**
Roanoke River	−31**	−13*	7	19*	16
SF Flathead River	−64**	−56**	−47**	−16	71**
Tennessee River	−29**	−5	15*	44**	22
Trinity River	95**	99**	98**	79**	88**
Westfield River	3	5	−1	8	17
Wynoochee River	110**	111**	104**	80**	49**
Mean	68	79	83	76	59
Mean increase	124	126	119	86	70
Mean decrease	−44	−37	−31	−15	−40

[a] If a significant difference exists between the two periods at the 5% level, it is designated with *, if a significant difference exists between the two periods at the 1% level, it is designated with **.

1-day minimum and maximum flows (Table 8). When this analysis is applied to the remaining sites, results indicate that the most significant effects manifest for the timing of 1-day minimum flows. For 1-day minimum flows, the mean shift in the expected date is 52 days; and for some sites, the effect is as great as 175 days (Tennessee River). The date of 1-day maximum flows has also changed but not as dramatically as has the 1-day minimum flow. For high flows, the average shift has been on the order of ~30-day.

3.4. Controls on hydrologic response

Using stepwise regression models, changes in the 32 IHA response variables were individually regressed against various climatic measures and dam characteristics. As these data indicate, the hydrologic responses to impoundment reflect the various engineering, regional, and climatic controls; and no single picture immediately emerges (Table 9). For minimum flows, the regression model only characterizes the change in 1-day minimum flows and none of the differences across the other flow durations could be significantly explained by the various climatic and dam characteristics. For high flows, significant relationships exist, but the explanatory independent variables change depending on which flow duration is evaluated. For shorter duration events (1–3 days), location, especially latitude, controls the magnitude and direction of difference. At longer durations, climate, especially measures of precipitation variability, control the magnitude and direction of difference.

Climatic and locational variables also best explain the differences in monthly streamflow, although the relative explanation depends on which months or seasons are evaluated. Precipitation variability best explains differences in late winter and mid-summer mean monthly runoff. September mean monthly flow manifested in the largest number of sites showing a significant difference to impoundment (Table 6), and variations in longitude best explain that trend (Table 9). Moving westward across the US generates a

Table 5
Percent difference in the means between pre-impact and post-impact conditions for the number of hydrograph reversals, hydrograph rise rate, and hydrograph fall rate[a]

Station	Percent change, reversals	Percent change, rise rate	Percent change, fall rate
Bill Williams River	7	−81*	−55
Chattahoochee River	35**	−31**	25*
Clinch River	94**	−51**	−11
Colorado River (AZ)	77**	22*	62**
Colorado River (TX)	32**	−92**	−90**
Cowlitz River	47**	−62**	−38
Coyote Creek	39**	−91**	−79**
Crooked Creek	−42**	−42**	0
Iowa River	−17**	−2	−3
Kaskaskia River	46**	−47**	−30**
Leon River	53**	−78**	−54**
NF King River	−27**	−76**	−66**
North Santiam River	67**	−55**	−25**
Olentangy River	−2	−22*	26*
Pound River	−13**	−32**	20*
Roanoke River	52**	−38**	−1
SF Flathead River	161**	78**	170**
Tennessee River	73**	−36**	11
Trinity River	42**	−90**	−83**
Westfield River	−3	−22**	−15*
Wynoochee River	0	−29**	−14
Mean	34	−52	−27
Mean increase	55	50	52
Mean decrease	−17	−48	−40

[a] If a significant difference exists between the two periods at the 5% level, it is designated with *; if a significant difference exists between the two periods at the 1% level, it is designated with **.

significant increase in monthly September flow, although it is a weak relationship ($R^2=0.18$).

To explain the magnitude and direction of difference for hydrograph features, dam characteristics, generally in combination with climatic variables, emerge as important variables. The number of hydrograph reversals, which have increased significantly following impoundment (Table 5), has occurred primarily in large, humid basins with abundant maximum reservoir storage (Table 9). Changes in the rates of discharge variation (i.e. rise rates and fall rates) depend more on locational and climatic variables. Rise rates have declined following impoundment, with most of the decline occurring in either small watersheds or in rivers in the western US. For high flows, the average duration (in days) above the pre-dam 75th percentile has tended to decrease (Table 6). That decrease seems best explained by temperature variability and dam maximum storage capacity. Changes in the date of the 1-day maximum discharge are controlled by mean annual temperature and its coefficient of variation. Sites in warm regions where snowmelt is not part of the hydrologic regime, like the Roanoke River in North Carolina or the Chattahoochee River in Georgia, have large deviations in the date of the 1-day maximum flow following impoundment. This effect is compounded in sites that have a minimal range of temperature through the year.

Consistent with the lack of generality in stepwise regression analyses, we were largely unable to statistically discriminate among types of dams of geographic locations based on hydrologic responses to dams. No statistically significant discriminant function was associated with primary dam function (Wilk's $\lambda=0.147$; $F_{[18,20]}=1.79$, $p>0.05$). For geographic location, k-means cluster analysis identified three groups based on latitude and longitude:

i) Northern Rocky Mountain and Pacific Northwest/Pacific Coast regions (seven stations);
ii) Eastern and central regions (ten stations;) and
iii) Southwest (Arizona and Texas) (four stations).

We found no statistically significant discriminant function associated with these three geographic clusters (Wilk's $\lambda=0.162$ $F_{[18,20]}=1.654$, $p>0.05$).

4. Discussion

4.1. Effects of type of dam or hydroclimatic region

This analysis indicates the pervasive, broad-scale effects of dams on the wide range of hydrologic parameters measured by the Indicators of Hydrologic Alteration, and the hydrologic shifts of dams identified herein may significantly affect river and riparian systems. While a number of studies have used IHA to examine individual dams or watersheds (Richter et al., 1996; Magilligan and Nislow, 2001), this study represents the first nationwide assessment using these techniques. As such, it reveals important information on the scale and generality of hydrologic alteration and on the ability of IHA and similar gage-record-

Table 6
Percent difference in the means between pre-impact and post-impact conditions for the low pulse number, low pulse length, high pulse number and high pulse length[a]

Station	Percent change in low pulse number	Percent change in low pulse length	Percent change in hi pulse number	Percent change in hi pulse length
Bill Williams River	−60**	−15	−45**	157*
Chattahoochee River	301**	−57**	75**	−32**
Clinch River	159**	−16	55**	10
Colorado River (AZ)	25	−56*	186**	−85**
Colorado River (TX)	7	−10	−45**	−12
Cowlitz River	−25	−29	−19	44
Coyote Creek	−29	−68**	10	54**
Crooked Creek	−49**	52**	−13	39**
Iowa River	−51**	40	24*	22
Kaskaskia River	0	−1	−27**	179**
Leon River	58*	68*	−38**	18
NF King River	−24	−3	−65**	−89**
North Santiam River	−69**	−90**	−5	11
Olentangy River	−6	−54**	26**	−18*
Pound River	−86**	−43	22*	−7
Roanoke River	209**	−53**	36**	−3
SF Flathead River	400**	−40*	749**	−81**
Tennessee River	105**	−68**	90**	−28**
Trinity River	−46**	64	−87**	−49**
Westfield River	−5	1	3	2
Wynoochee River	6	−39**	−24**	9
Mean	39	−20	43	7
Mean Increase	141	45	116	49
Mean Decrease	−38	−40	−37	−40

[a] If a significant difference exists between the two periods at the 5% level, it is designated with *, if a significant difference exists between the two periods at the 1% level, it is designated with **.

based approaches to measure and detect these fundamental changes.

Numerous hydrologic parameters showed consistent differences from impoundment, both in magnitude and direction of the effect, irrespective of type of dam. In some circumstances, however, hydrologic parameters were consistently different, but the magnitude or direction of the effect varied amongst types of dams. The most consistent effect, of course, occurred in changes in maximum flows where 20 of the 21 sites had significantly reduced peak flows following impoundment, irrespective of type of dam or region. This consistent relationship, however, attenuates with increasing flow durations with less than half the sites experiencing significant effects at flow durations exceeding weekly flow durations.

Changes in low flows seem to be the most consistent and profound adjustments for this analysis. Significant changes in the magnitude of low flow are expressed throughout all durations from the 1-day through the 90-day, and the impact gets progressively more consistent in direction with increasing flow durations (Table 4). At the shorter durations, these results indicate that the commonly held belief that impoundment leads to increased minimum flows is not necessarily accurate. One-third of the significant responses for 1-day minimum flows indicate a decreased magnitude of minimum flows following impoundment, and the effect does not necessarily relate to dam function, size, or location. Dams as diverse as the Douglas Dam on the Tennessee River and the Belton Dam on the Leon River in Texas responded similarly to impoundment despite being in different climatic regions and having different operational functions. For those sites increasing 1-day flows, a lack of a regional or climatic control exists (Table 4).

Consistent trends in the number of hydrograph reversals also showed significant effects, generally

Table 7
Percent difference in the means between pre-impact and post-impact conditions for mean monthly streamflow[a]

River	Percent change, October flow	Percent change, November flow	Percent change, December flow	Percent change, January flow	Percent change, February flow	Percent change, March flow	Percent change, April flow	Percent change, May flow	Percent change, June flow	Percent change, July flow	Percent change, August flow	Percent change, September flow	Number of significant differences
Bill Williams	479*	43	−64	12	115	48	−26	472*	601*	922	0	282*	3
Chattahoochee	43**	34**	−30*	−27*	−27**	−23*	−1	2	12	7	42**	65**	8
Clinch	181**	54*	−3	−33**	−36**	−59**	−62**	−48**	7	40**	102**	219**	10
Colorado (AZ)	33*	2	−32	−11	84**	25*	−33**	−66**	−68**	−23*	52**	65**	9
Colorado (TX)	−77**	−66*	−73	6	−28	−30	−91**	−90**	−76**	−87**	−68**	−79**	8
Cowlitz	25	11	21	31**	12	2	−27**	−39**	−21*	2	34**	64**	6
Coyote	310**	271**	−29	−80**	−80**	−71**	1	132**	219**	353**	387**	376**	10
Crooked	4	−29	−2	−13	6	5	26	12	17	19	−16	−31	0
Iowa	37	75**	123*	48	24	13	59**	48*	33	135**	161**	62	6
Kaskaskia	−16	−5	234**	57	53*	27	−5	−21	−5	9	40	86*	3
Leon	−23	−5	−35	−1	−37	7	−26	−41	22	118**	146	−59	1
NF King	10	−54	−74*	−60**	−72**	−85**	−93**	−93**	−79**	−43	−18*	128**	8
North Santiam	79**	14	−2	21	−12	−21*	−26**	−14	−8	7	43**	107**	5
Olentangy	−29	34	14	−27	−1	2	−3	19	4	109*	57	−36	1
Pound	359**	120**	16	−1	−8	−16	−32**	16	49	−25	7	142**	4
Roanoke	1	13	−6	−18	−12	−12	5	33*	14	−17	−27	−7	1
SF Flathead	184**	108**	215**	246**	175**	126**	−17	−83**	−73**	−19	95**	247**	10
Tennessee	79**	84**	34*	−6	−17	−40**	−41**	−29**	7	19	49**	93**	8
Trinity	−4	−59**	−70**	−60**	−75**	−72**	−79**	−78**	−64**	−37**	62**	102**	11
Westfield	23	8	4	−6	24	−11	4	16	19	11	18	−19	0
Wynoochee	−11	13	5	−14	−5	−11	−34**	−18*	5	31**	50**	46**	5
Mean	80	32	12	3	4	−9	−24	6	29	73	58	88	
Mean increase	123	59	74	60	62	28	19	83	78	127	84*	139	
Mean decrease	−27	−36	−35	−25	−32	−38	−37	−52	−49	−36	−26	−38	
Number of significant differences	10	9	7	7	8	9	11	13	8	9	12	15	

[a] If a significant difference exists between the two periods at the 5% level, it is designated with *; if a significant difference exists between the two periods at the 1% level, it is designated with **.

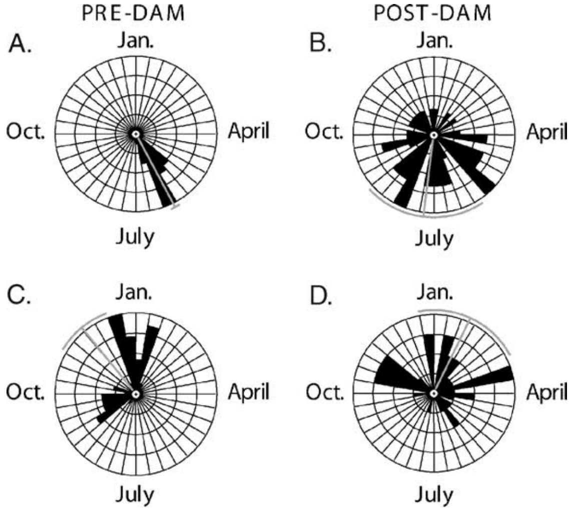

Fig. 3. Circular rose diagrams for the Colorado River by Lee's Ferry. The upper diagram is the circular histogram for the Julian date of the pre-impact (A) and post-impact (B) 1-day maximum flows. For the pre-impact condition, the sample size is 41 years. The class interval is 10 d and the number of events in the maximum class interval is 12. The vector mean date is May 31, with a 95% confidence interval of 4 days. For the post-impact period, the sample size is 38 years. The class interval is 10 days and the number of events in the maximum class interval is 3. The vector mean date is now July 3 and the 95% confidence interval has increased to 42 days. The bottom diagram is the circular histogram for the pre-impact (C) and post-impact (D) 1-day minimum flows. For the pre-impact condition, the sample size is 41 years. The class interval is 10 days and the number of events in the maximum class interval is 7. The vector mean date is November 16, and the 95% confidence interval is 20 days. For the post-impact period, the sample size is 38 years. The class interval is 10 days and the number of events in the maximum class interval is 4. The vector mean date has now shifted to January 25, and the 95% confidence interval has increased to 37 days. For each figure, the gray line from the diagram center is the vector mean date, and the gray curved line represents the 95% confidence interval.

irrespective of type of dam, with most sites generally increasing the number of reversals following impoundment. This would tend to occur in hydroclimatic regimes typified by one sustained runoff season, like snowmelt, that is now punctuated by storage and managed flow releases either for hydropower or flood control. For example, the Flathead River in Montana usually experienced 55 hydrograph reversals through the course of the year prior to impoundment, but now averages 155 reversals in the post-dam environment, an increase of 161% (Table 5). Even in non-snowmelt hydrologic regimes, the number of reversals can increase dramatically as a function of impoundment. The Chattahoochee River in north Georgia lies in the humid southeastern US where a strong bi-modal flood distribution exists (Lecce, 2000). The number of hydrograph reversals has increased 34% where, on average, it experienced 115 reversals pre-dam; and now hydrograph reversals commonly occur ~155 times a year.

For monthly flows, the effect of the type of dam strongly influences the magnitude and direction of the response. For small flood control dams, typical of Crooked Creek in Pennsylvania and the Westfield

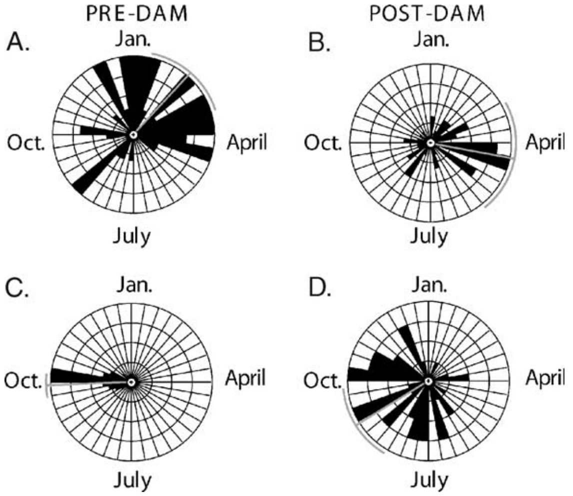

Fig. 4. Circular rose diagrams for the Chattahoochee River downstream of Buford Dam. The upper diagram is the circular histogram for the Julian date of the pre-impact (A) and post-impact (B) 1-day maximum flows. For the pre-impact condition, the sample size is 43 years. The class interval is 10 days and the number of events in the maximum class interval is 3. The vector mean date is February 19 and the 95% confidence interval is 30 days. For the post-impact period, the sample size is 44 years. The class interval is 10 days and the number of events in the maximum class interval is 6. The vector mean date is now April 11, and the 95% confidence interval is now 40 days. The bottom diagram is the circular histogram for the pre-impact (C) and post-impact (D) 1-day minimum flows. For the pre-impact condition, the sample size is 43 years. The class interval is 10 days and the number of events in the maximum class interval is 11. The vector mean date is September 26, and the 95% confidence interval is 9 days. For the post-impact period, the sample size is 44 years. The class interval is 10 days and the number of events in the maximum class interval is 6. The vector mean date is now August 26, and the 95% confidence interval has increased to 27 days. For each figure, the gray line from the diagram center is the vector mean date, and the gray curved line represents the 95% confidence interval.

Table 8
Changes in the vector mean date of 1-day minimum flow and 1-day maximum flow (using Eq. (2))

River	Pre-dam minimum vector mean, Julian date	Post-dam minimum vector mean, Julian date	# Days different	Pre-dam maximum vector mean, Julian date	Post-dam maximum vector mean, Julian date	# Days different
Bill Williams	211	118	93	6	47	41
Chattahoochee	265	234	31	40	105	65
Clinch	278	17	103	50	44	6
Colorado (AZ)	321	26	69	151	185	34
Colorado (TX)	211	203	8	179	207	28
Cowlitz	277	240	37	1	7	6
Coyote	267	8	105	47	149	102
Crooked	238	247	9	87	64	23
Iowa	289	271	18	106	113	7
Kaskaskia	280	265	15	119	62	57
Leon	260	257	3	138	153	15
NF King	364	342	22	134	105	29
North Santiam	268	221	47	11	360	16
Olentangy	253	186	67	71	66	5
Pound	264	331	67	60	65	5
Roanoke	268	331	63	10	65	55
SF Flathead	318	172	146	144	93	51
Tennessee	280	105	175	66	36	30
Trinity River	261	267	6	56	96	40
Westfield	245	246	1	84	94	10
Wynoochee	253	259	6	360	354	6
Mean			52			30

River in Massachusetts, in no month did the post-dam record significantly differ from the pre-dam monthly runoff regime. For the remaining single-function flood control structures (the Leon River in Texas and the Olentangy River in Ohio), only 1 month had post-dam flows that differed. Although these dams are in climatically different regions, the lone month where the difference occurred was July. Similarly, single-function flood control dams, except for the Olentangy River, seem to have the least response to the timing of 1-day minimum flows, generally with less than an 18-day shift in the date of 1-day minimum flow. The single-function flood control dams also have the least effect on shifting the 1-day maximum flows (<18 days), although the single-function flood control dam on the Kaskaskia River in Illinois generated one of largest shifts in the date of the 1-day maximum flow (57 days).

Sites that are single-function hydropower, or where hydropower generation is the dominant function in a multiple purpose reservoir, tend to have the greatest number of months where post-dam monthly runoff has been significantly modified. This is especially true in regions like the semi-arid southwestern US where a strong seasonality exists in runoff. At the extreme end, the monthly hydrologic regime of the Trinity River in California has been so disrupted by the combined irrigation and hydropower management of the dam, that only the mean monthly flows in October have not been significantly affected by impoundment and diversion.

Finding consistent trends by function of the dam proved difficult. The lack of consistency may result from several factors. First, differences in climate or management operation of the dam may dominate the relationship and overprint the effect of type of dam. This was also evident in earlier work where we investigated the effects of dams on the 2-year bankfull discharge (Magilligan et al., 2003). Using a similar pan-US dataset, that analysis indicates that the within-dam type variation exceeds the between-dam type variation in explaining bankfull discharge reductions following impoundment. Second, the limited number of sites meeting the selection criteria makes it difficult to find a critical mass of different types of dams while controlling for climatic region.

Table 9
Results from the stepwise regression analysis

I. Magnitude and duration	
1-day Min.	Watershed Size
1-day, 3-day Max.	Location (**Latitude**, Longitude)
7-day Max.	Climate (**Coefficient of Variation Precip.**, Location (**Latitude**)
30-day, 90-day Max.	Climate (**Coefficient of Variation Precip.**)
Baseflow	Climate (**Coefficient of Variation Precip.**, St. Dev. Precip., Coefficient of Variation Temp.)
II. Rates of change	
High pulse length	Climate (Coefficient of Variation Temp.), Dam Characteristics (Max. Storage)
Rise rate	Location (**Latitude**, Longitude), Watershed Size
Fall rate	Climate (**Coefficient of Variation Precip.**, St. Dev. Precip, Coefficient of Variation Temp.)
Reversals	Watershed Size, Dam Characteristics (**Max. Storage**), Climate (**Mean Annual Precip.**)
III. Monthly streamflow changes	
December	Location (**Latitude**)
January	Watershed Size, Dam Characteristics (**Max. Storage**), Location (**Latitude**)
February, March	Climate (**Precip. Variability**) and Location (**Latitude**)
May, June	Climate (**Mean Annual Temp.**) and Watershed Size
July	Climate (**Coefficient of Variation Precip.**)
September	Location (**Longitude**)
IV. Timing	
Differences in Date of max. flow	Climate (**Mean Annual Temp**., Coefficient of Variation Temp.)

Rather than focusing specifically on the output from the regression model for each of the IHA parameters, this table portrays the dominant trends. Predictors shown in bold indicate the dominant control in explaining the magnitude and direction of the IHA dependent variable.

4.2. Ecological implications

The hydrologic changes described herein should manifest in significant ecological adjustments. Although we did not specifically address the ecological effects of impoundment, the hydrologic effects determined herein point to the direction and magnitude of those effects and help identify which types of basins may generate which type of responses. The magnitude of hydrologic changes shown from this analysis suggests that a similarly profound ecological shift should result, as the greater the deviation in flow regime from pre-disturbance conditions the greater the expected ecological response (Poff and Hart, 2002). For example, the 52-day mean shift in the minimum flow represents a dramatic revision in the expected temporal occurrence. Extreme conditions put important stresses on biological communities and, within some bounds of tolerance, can greatly enhance biodiversity. Dramatic shifts such as in the timing of minimum or maximum flows can be greatly outside the bounds of natural variation and can greatly diminish aquatic biodiversity.

Disturbance is an important ecological component. Adjustments to the magnitude and timing of bed disturbing flows may diminish faunal heterogeneity of the channel bed that may ripple up community food webs (Power et al., 1996). Macroinvertebrates and benthic fishes respond quickly to hydrogeomorphic disturbance and are usually good indicators of environmental degradation (Wootton et al., 1996). These populations require some modicum of disturbance to maintain diversity. These key species fare poorly in environments where high flows have been reduced and where accelerated channel bed sedimentation is likely to be enhanced, circumstances that commonly occur downstream of dams. The most obvious forms of degradation occur when critical components of habitat, such as spawning gravels and cobble surfaces, are physically covered by fines that ultimately decreases intergravel oxygen and reducing or eliminating the quality and quantity of habitat for fish, macroinvertebrates, and algae (Lisle, 1989; Waters, 1995). Increased deposition of fine sediments has been repeatedly shown to decrease macroinvertebrate diversity and abundance (Richards and Bacon, 1994; Waters, 1995; Angradi, 1999) and to reduce the survival of benthic-spawning fishes (Hicks et al., 1991; Wu, 2000). In addition, reduced frequency of substrate disturbance, caused by flow regulation, can reduce invertebrate diversity by increasing the degree of competitive exclusion by competitively dominant but disturbance-vulnerable species (Wootton et al., 1996). With reference to impoundments on tributaries (typical of flood control structures), many salmonids depend on unconsolidated gravel sediments associated with riffles as spawning sites (Geist and Dauble, 1998). Degradation of these sites by the elimination of bed disturbing flows due to impoundment may therefore reduce overall productivity and diversity.

5. Conclusions

Results presented herein are some of the few to characterize the hydrologic effects of impoundment across multiple sites and climatic regions that utilize an array of hydrologic parameters. The diverse parameters in the IHA model may help identify which hydrologic variable (or sets of variables) shift as a result of impoundment and helps force scientists and mangers to consider ecologically important parameters that are not usually on the immediate radar screen. For some sites, changes in "traditional" hydrologic characteristics, like 1-day minimum flows, may not be dramatic; but other variables, like the timing of 1-day minimum flows, may register a significant adjustment. Similarly, prescriptive policies for management, focusing solely on one hydrologic variable, may miss attaining the ultimate goal of preserving ecological integrity if the entire panoply of hydrologic adjustments are not adequately incorporated. This study reinforces the view espoused by Poff et al. (1997) that management strategies are necessary that best approximate the pre-impact natural flow regime. The results using IHA can help identify pre-impact conditions and can provide an important mechanism for establishing pre-impact base conditions.

Several limitations of this technique exist, however, especially in the few number of sites that can meet the requisite sampling criteria established by Richter et al. (1996). The limited number of sites across the US meeting these requirements and the limited number of dams in each functional category for a given hydroclimatic region make it difficult to actualize a robust statistical analysis. Although stream gage records represent some of the best long-term environmental datasets available, the number of records that fulfill length-of-record requirements seems to be inadequate for IHA-style approaches. For a given site, however, this technique does seem to adequately portray the magnitude, direction, and range of hydrologic responses, especially when augmented with orientation statistics.

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