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Damming the prairie: Human alteration of Great Plains river regimes

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SUMMARY

Many studies have investigated post-impoundment hydrologic regime alteration; however, the Great Plains of the United States are often excluded from these analyses. The goal of this analysis was to evaluate the pre and post-impact hydrologic regimes of Great Plains rivers. The hydrologic records of nine large rivers were analyzed to quantify the magnitude, duration, and direction of hydrologic alteration attributable to impoundment. An additional tenth system, the Red River of the North, was included in the analysis to provide an example of a comparable regional hydrologic regime without the presence of impoundments on the main-stem of the network. Hydrologic regimes were analyzed using the Indicators of Hydrologic Alteration, a model that estimates 33 hydrologic and ecologically relevant parameters. For many of the parameters, the magnitude, duration, and direction were similar across the systems. The results showed a significant increase in the 1 through 90 day minimum discharges and a significant decrease in the 1 through 90 day maximum discharge; though the magnitude of alteration decreased with increased temporal averaging. The most dramatic alterations were large increases in the number of annual hydrograph reversals and faster rise and fall rates. Results of this study are the first to quantify the widespread hydrologic alteration of Great Plains rivers following impoundment.

1. Introduction

Dams have been a feature in the fluvial landscape for at least the last two millennia. However, the construction of large modern dams produced a dramatic change in the magnitude of hydrologic, geomorphologic, and ecological impacts on large rivers. Although the first large American dams were constructed during the early 1900s, the 1960s represent a very significant dam building era in the United States, when a quarter of all existing US dams were constructed (US Army Corps of Engineers, 1996). Dams provide numerous societal benefits, including reliable water supplies, recreation, flood control, navigation, hydroelectric power, and irrigation (World Commission on Dams (WCD), 2000). However, dams are also the most significant source of anthropogenic hydrologic disturbance on rivers in the United States (Graf, 1999) and worldwide (Dynesius and Nilsso, 1994; Vorosmarty et al., 1997). River ecosystems have evolved within the context of the natural hydrologic regime (Lytle and Poff, 2004), adapting to patterns of variation in the delivery of water, nutrients, energy, sediments, and habitats, but now many of these regime patterns have been fundamentally altered by dams (Sparks et al., 1998; WCD, 2000; Nislow et al., 2002).

The first scientific studies of downstream dam impacts began to emerge in the 1980s as the degree of post-impoundment downstream ecosystem alteration became increasingly apparent (Baxter, 1977; Graf, 2005). This magnified interest in how dams affect the hydrology, geomorphology, and ecology of rivers, and produced a concentrated effort to understand the impact of impoundments. Since that time, there have been numerous assessments of the impacts of dams on rivers (e.g. Graf, 2006). To address the need for consistency in assessments, Richter et al. (1996) developed an analytical model, the Indicators of Hydrologic Alteration (IHA), to statistically characterize the variability in hydrologic regimes with biologically relevant attributes and quantify the hydrologic alterations associated with a disturbance, often a dam. The IHA model has been widely used to determine hydrologic alteration by individual dams, series of dams on a river network (Galat and Lipkin, 2000), and within multi-network national studies (Magilligan and Nislow, 2005). Results of these studies have been mixed, with wide variation in the nature of hydrologic regime alteration. Some commonalities in all cases are the presence of significant changes in the number of discharge reversals and in rise and fall rates of the hydrograph (Galat and Lipkin, 2000; Magilligan and Nislow, 2005; Perkin and Bonner, 2011). Analysis of the parameters estimated by IHA indicates that there is redundancy in the parameters (Olden and Poff, 2003); however, IHA still provide a useful estimation of hydrologic parameters.

While post-impoundment impacts on Great Plains river ecosystems have been identified, no study has yet examined in detail the specific impoundment-driven changes to the hydrologic regime that are, in part, driving the decline of these ecosystems. Without

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a comprehensive understanding of the nature of the hydrologic regime alterations, sound recommendations cannot be made to address dam management modifications for in-stream discharge needs, habitat maintenance, channel stability, or other ecosystem management objectives. We address this gap in knowledge by assessing hydrologic regime shifts for their type, duration, direction, and magnitude using IHA for ten river systems distributed across the Great Plains region. Due to the varying climate throughout the Great Plains region, it is difficult to differentiate between climatic and anthropogenic sources of hydrologic alteration of rivers. We tested the hypotheses that impoundment would result in: (1) muted discharge magnitudes at both the high and low extremes, (2) reduction of low discharge durations, and (3) increased rise and fall rates. The results of this research illustrate the extent to which impoundments have affected the hydrology of Great Plains rivers and document opportunities for naturalization of Great Plains river discharge regimes.

2. Regional context

Despite the presence of numerous large flood-control reservoirs in the Great Plains, no study has regionally assessed the post-impoundment alteration of the region's hydrologic regimes. The Great Plains of the United States encompasses the area from the Prairie Provinces of Canada to the Rio Grande, and from the Rocky Mountains to the Missouri River; including the majority of ten US States: Colorado, Kansas, Montana, North Dakota, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. This region is semi-arid and historically dominated by grassland biomes. Generally, most rivers flow eastward within the Arkansas, Missouri, and Red River of the south drainage basins and eventually drain into the Mississippi River; however, there are many exceptions including the Colorado River and Rio Grande draining to the Gulf of Mexico, and the Red River of the North draining northward into Lake Winnipeg, Canada. Channels are wide, sand bedded, and with high turbidity. Planforms typically range from semi-braided to meandering.

The rivers of the Great Plains are perhaps the most scientifically overlooked streams in the continental United States (Matthews, 1988), yet they are dynamic and unique ecosystems contain species that need to be conserved, are important for migratory waterfowl, and support fisheries and recreational uses. The geographical setting of the region is in the arid rain shadow of the Rocky Mountains, which produces characteristically flashy hydrologic regimes, with large floods interspersed within periods of prolonged drought (Dodds et al., 2004). The typical annual regime varies somewhat with latitude and longitude through the Great Plains region, with more northern systems experiencing an early snow-melt flood pulse and a later spring/early summer convective storm driven flood pulse while. More southerly systems are influences by monsoons, hurricanes, and dry line thunderstorms. The natural range of hydrologic extremes has been altered by anthropogenic activities such as the construction of flood-control impoundments, unsustainable groundwater extraction practices, and widespread land cover conversion of watersheds from grassland to agriculture. Global climate change is likely to affect these streams even more with general circulation models predicting more frequent intense precipitation events with longer intervening dry periods (Knapp et al., 2002; Milley et al., 2005). The unique assemblage of aquatic fauna found in Great Plains rivers is adapted to frequent intermittence of smaller streams, historically high flood frequencies with low predictability, and to periodic episodes of extreme drought that produce long periods of no flow, especially in smaller streams and rivers as well as to high sediment loads and turbidity in larger rivers (Poff and Ward, 1989; Dodds et al., 2004).

Riparian vegetation patterns are closely associated with the geomorphological dynamics of the channel and floodplain surfaces (e.g. Hupp and Osterkamp, 1985). It is unsurprising then that post-impoundment riparian vegetation changes are also closely linked to both geomorphic and hydrologic adjustments following impoundment. Previously braided rivers typically experience an initial pulse of recruitment by pioneer species (for example, the dramatic increase in Populis–Salix woodlands along the Platte River) as vegetation occupies the formerly active channel areas and areas that were frequently disturbed floodplain become available for colonization. This phase is followed by declines in pioneer species and replacement by mature woodland species. Along previously meandering rivers, recruitment of pioneer species dramatically declines following impoundment due to the reduction in channel migration, point bar formation and floodplain disturbance (e.g. Johnson, 1998). Hydrologic regime components critical to vegetation establishment include timing and magnitude of peak flows, fall rate, and base flow magnitudes (Shaforth et al., 1998).

Ecological and geomorphological studies have documented that impoundment construction has profoundly impacted river ecogeomorphology in the Great Plains. The post-impoundment morphologic responses vary somewhat depending on the initial pre-impoundment conditions as well as the local surficial geology, but Great Plains rivers are especially susceptible to downstream effects of dams because they are typically fine-grained alluvial rivers without confining canyon walls (Graf, 2005). In the absence of flow augmentation, meandering rivers tend to decrease their migration rates and incise, while braided rivers dramatically narrow and may deepen into a single-threaded meandering planform (Williams and Wolman, 1984; Friedman et al., 1998). With flow augmentation, meandering channels exhibit increases in width-depth ratios, substrate size, and exposed depositional bar area (Kellerhals et al., 1979; Dominick and O'Neill, 1998) after which bed degradation may ensue if channel armoring is absent or broken (Church, 1995). Regulated Great Plains river reaches have up to 91% less standard active area than unregulated rivers (Williams, 1978; Graf, 2006).

3. Methods

3.1. System selection

To analyze post-impoundment hydrologic alteration within the Great Plains, selected systems: (1) were within the Great Plains physiographic region, (2) had US Geological Survey streamflow gages immediately downstream of a main-stem dam with mean daily discharge data for at least 15 years pre-impoundment and 30 years post-impoundment, and (3) did not have discharge diversions prior to the dam construction. While it would have been preferable to use systems with greater than 15 years of pre-impoundment discharge records, these data do not exist. During the system selection process it became apparent that most Great Plains USGS gages were constructed concurrently with dams, and many of these gages were decommissioned soon after dams were completed, greatly limiting the number of acceptable data sets. Nine gaged systems met our selection criteria, located on the Arkansas, Canadian, Kansas, Lower Missouri, Upper Missouri, Pecos, Red (of the South), Republican, and Wakarusa Rivers (Fig. 1). We also sought unregulated "control" systems, but no gaged unregulated large rivers remain in the Great Plains. As an alternative, we included a gage site on the unregulated main-stem of the Red River of the North; however, the upstream major tributaries of this system are impounded. This tenth system represents the best available opportunity to assess how current discharge regimes compare to historical (defined as pre 1968 following Perkin and

Fig. 1. Location of systems used for analysis, where gray circles indicate gage sites used for analysis. The boundary of the Great Plains USA is delineated in light gray.

Gido, 2011) discharge regimes for the region. The dams in this analysis are not run of the river dams and as such any flow reversals are due to management of the dam and are not a result of the a short dam height.

3.2. Indicators of hydrologic alteration

Gage records were analyzed using the IHA model developed by the Nature Conservancy (Richter et al., 1996) to determine hydrologic shifts of Great Plains Rivers in response to dam construction. Parameters were developed by Richter et al. (1996) because of their close relationship to ecological functioning as well as for their ability to reflect human induced changes to discharge regimes for a wide range of disturbances (Mathews and Richter, 2007). Analyses were conducted on mean daily discharges for the water year (October–September) for the period of record prior to dam construction (reference) and then again after the dam construction was completed (disturbance). In the case of the Red River of the North, historic (pre 1968) and current hydrologic conditions were evaluated. IHA measures central tendency (mean, median) and dispersion (range, standard deviation, percentiles, coefficient of variation and coefficient of dispersion) to determine the inter-annual variation between the two periods (Richter et al., 1996) to compare reference and disturbance periods. The IHA also provides information on discharge regimes without the presence of a disturbance. From mean daily discharge, IHA computes 33 intra- and inter-annual flow parameters that fall into five major groups: (1) magnitude of monthly stream discharge conditions, (2) magnitude and duration of annual extreme discharge conditions, (3) timing of annual extreme discharge conditions, (4) frequency and duration of high and low pulses, and (5) rate and frequency of discharge condition change.

Group 1 includes the magnitude and timing of the mean value of discharge for each month. Group 2 includes the magnitude and duration of the 1, 3, 7, 30 and 90 day mean annual minimum and maximum discharge. Group 3 reports the Julian date of each 1 day annual minimum and maximum discharge. Group 4 is the magnitude, frequency, number, and duration of the number of low and high pulses within each year. Pulses are a sequence of days in which discharge exceeds the 75th or falls below the 25th percentile of the pre-impoundment ranked daily discharges. Group 5 includes the means of the positive and negative differences between consecutive daily means as well as the number of hydrograph falls, rises, and reversals. A rise is a sequence of continuously rising mean daily discharges and a fall is a sequence of continuously decreasing mean daily discharges. Reversals are a change in a sequence from a fall to a rise or vice versa. Because IHA uses mean daily discharges, reversals are not at the diel scale; rather, it measures the day to day variation in hydrographs. Zero discharge days are excluded from this analysis because many study systems are large perennial rivers that do not typically experience zero flow days because of their size, but might experience zero discharge days where impoundments are coupled with groundwater withdrawal (e.g. Perkin and Gido, 2011).

3.3. Statistical analysis

Student's paired *t*-tests were used to determine if means for each of the response variables were statistically different from one another where significance was defined as $p \leqslant 0.05$. A principle component analysis (PCA) was used to capture variation in changes to the parameters estimated by IHA for the pre and post-impoundment. A correlation matrix was constructed that allowed for removal of IHA estimated parameters that were highly correlated ($r > 0.8$) from the PCA analysis. The second axis of the PCA distinguishes rivers and the third axis distinguishes the natural and regulated river regimes. Using the PCA we were able to determine a coarse relative magnitude of system alteration with which to compare the 10 study systems.

4. Results

Selection criteria provided ten gaging stations in the Great Plains that were distributed over this physiographic region (Fig. 1), and the effects of these dams on hydrological indices were captured with IHA. In some cases, these impoundments altered the total annual discharge dramatically (Table 1). The Canadian River experienced an 88% decrease in mean annual discharge, while

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Table 1
Characteristics of systems used in the analysis, where Q is discharge in cubic meters per second.

River	State	Dam(s)	Dam height (m)	Reservoir storage (km^3)	Mean annual Q pre-impact	Mean annual Q post-impact	% Change
Arkansas	CO	John Martin	36.0	0.75	8.27	3.40	-59^{**}
Canadian	NM	Ute	40.2	0.50	9.66	1.19	-88^{**}
Kansas	KS	Tuttle and Milford	47.9 and 44.8	2.78 and 1.41	104.87	147.42	41^{**}
LowerMissouri	NE	Gavins Point	14.3	0.67	727.18	735.11	1
UpperMissouri	MT	Garrison	64.0	30.21	624.10	624.39	0
Pecos	NM	Brantley	43.9	1.19	3.31	4.39	33^{**}
Red of the North	ND	None	–	–	15.15	33.73	123^{**}
Red of the South	TX	Denison	50.3	6.40	137.25	138.13	1
Republican	NE	Harlan County Lake Dam	32.6	1.02	25.06	8.81	-65^{**}
Wakarusa	KS	Clinton Lake	35.4	0.45	5.32	7.62	44^{**}

** Significant difference between the two periods at the 1% level exists.

the mean annual discharges of the Kansas River and the Red River of the North have increased by 44%, and 123%, respectively. However, in the Upper and Lower Missouri Rivers and the Red River of the South, the mean annual discharge has been altered by only 1% or less (p 0.32, 0.99, 0.83, respectively).

4.1. Magnitude of monthly stream discharge conditions

Impoundment produced stark variations in the timing of monthly discharge releases from those observed in the reference regimes, although there was no uniform pattern of variation across the study region. In some cases, such as the Missouri River, discharges increased in August through February (Table 2; Fig. 2). In contrast, the Red River of the North experienced its greatest increases in discharge in February and March. There was not a strong pattern of change in mean monthly discharges for the other study sites even though many of them were significantly altered. The Arkansas, Canadian, and Republican rivers all experienced a decrease in every month's mean discharge, whereas the Wakarusa River and the Red River of the North experienced an increase in every month's mean discharge. Six of the rivers in the study experience a significant alteration in their monthly discharges for each month.

4.2. Magnitude and duration of annual extreme discharge conditions

The volume of water released through impoundments has altered the magnitude of the 1, 3, 7, 30 and 90-day mean annual minimum and maximum discharges dramatically (Tables 3 and 4). The magnitude of the 1-day minimum discharge increased, on average, by 124%. The mean annual 1-day minimum discharge increased at seven of the ten systems included in this study, five of which are statistically significant. The Wakarusa River experienced the greatest alteration in the minimum discharges with an average increase of over 230% for all the discharge periods calculated by IHA with the 1, 3 and 7-day discharges have all increased by over 300%, the 30-day by 120%, and the 90-day by 96%. The Pecos River was the least altered, with an average decrease of 10% in the minimum discharge, none of which are different from the pre-dam period. The influence of the impoundments with the minimum discharges decreased as the period the discharge was determined over increases.

Maximum discharges also shifted, though not to the degree of minimum discharges (Table 4). The Canadian River was most altered, with an over 80% decrease in all of the maximum discharges calculated by IHA. The Red River of the North was the only system to experience significant increases in each of the maximum discharge categories. The Pecos River was again the least altered, with an average alteration of 16%, none of which were significantly different. None of the nine main-stem dammed rivers included in this study experienced an increase in the 1-day maximum discharge. Similar to the minimum discharges, as the time frame of interest for mean annual maximum discharge increased, the impact of the impoundments on maximum discharges diminished. However, the Red River of the North again stood apart with significant increases among all maximum discharge categories.

4.3. Timing of annual extreme discharge conditions

No clustering of timing for 1-day minimum or 1-day maximum discharge days was observed for the study region, neither for reference nor disturbance regimes (Table 5). However, the mean date of

Table 2
Percent change in mean monthly flows following impact, where Q is discharge.

	October Q	November Q	December Q	January Q	February Q	March Q	April Q	May Q	June Q	July Q	August Q	September Q
Arkansas	-69^{**}	-73^{**}	-70^{**}	-72^{**}	-65^{**}	-28^{*}	-55^{*}	-60^{**}	-68^{**}	-25^{**}	-69^{**}	-38^{**}
Canadian	-92^{**}	-68^{**}	-75^{**}	-82^{**}	-37^{**}	-52^{**}	-93^{**}	-93^{**}	-93^{**}	-77^{**}	-84^{**}	-88^{**}
Kansas	38^{**}	90^{**}	121^{**}	62^{**}	52^{**}	110^{**}	87^{**}	53^{**}	-19^{**}	76^{**}	36^{**}	-3
Lower Missouri	68^{**}	61^{**}	82^{**}	57^{**}	37^{**}	-28^{**}	-43^{**}	-6^{**}	-44^{**}	-25^{**}	46^{**}	64^{**}
Upper Missouri	14^{**}	22^{**}	51^{**}	71^{**}	74^{**}	-15^{**}	-10^{*}	-15^{**}	-50^{**}	-27^{**}	46^{**}	49^{**}
Pecos	75^{**}	239^{**}	99^{**}	-5	34^{**}	43^{**}	0	1	51^{**}	45^{**}	13^{**}	11
Red of the North	138^{**}	140^{**}	124^{**}	140^{**}	179^{**}	192^{**}	139^{**}	102^{**}	84^{**}	98^{**}	97^{**}	126^{**}
Red of the South	-12	80^{**}	3	22^{**}	18^{*}	22^{**}	-5	-36^{**}	31^{**}	33^{**}	33^{**}	-51^{**}
Republican	-50	-45^{**}	-52^{**}	-55^{**}	-58^{**}	-55^{**}	-56^{**}	-62^{**}	-82^{**}	-62^{**}	-63^{**}	-68^{**}
Wakarusa	78^{**}	60^{**}	92^{**}	44^{**}	51^{**}	53^{**}	21^{*}	79^{**}	22^{*}	6	42^{*}	104^{**}
Mean decrease	56	62	66	54	53	38	44	45	59	43	72	50
Mean increase	69	99	82	66	64	84	82	59	47	51	43	71

* Significant difference between the two periods at the 5% level exists.
** Significant difference between the two periods at the 1% level exists.

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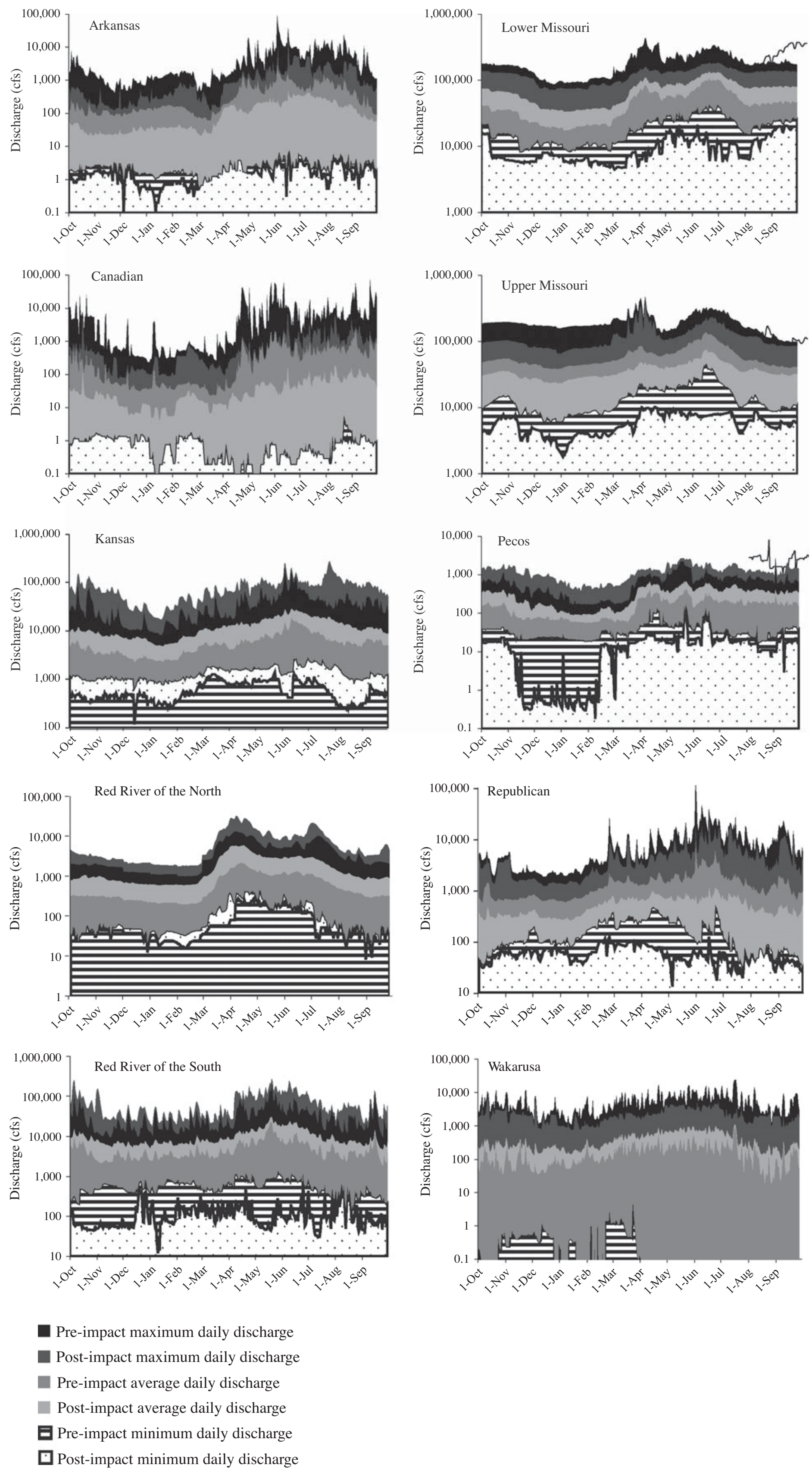

Fig. 2. Mean daily discharge for the pre-impact and post-impact time periods.

the 1-day minimum discharge of all the rivers in this analysis shifted by 82 days, with the Canadian, Kansas, and Pecos Rivers all shifting more than 120 days. The Kansas and Pecos river 1-day minimum discharge shifted from late May and early June to

Table 3
Percent change in the means of pre and post-impact minimum discharges, where Q is discharge.

River	1-Day min Q	3-Day min Q	7-Day min Q	30-Day min Q	90-Day min Q
Arkansas	249**	202**	165**	49	−9
Canadian	6	9	6	12	52*
Kansas	29	29	29	22	39*
Lower Missouri	96**	96**	95**	75**	53**
Upper Missouri	119**	128**	128**	108**	73**
Pecos	−18	−13	−11	−8	−2
Red of the North	131**	138**	143**	162**	137**
Red of the South	−76**	−51**	−7	34	9
Republican	−26*	−30*	−32*	−41**	−57**
Wakarusa	324**	318**	312**	120**	96*
Mean decrease	40	31	17	25	30
Mean increase	124	120	114	66	66

* Significant difference between the two periods at the 5% level exists.
** Significant difference between the two periods at the 1% level exists.

Table 4
Percent change in the means of pre and post-impact maximum discharges, where Q is discharge.

River	1-Day max Q	3-Day max Q	7-Day max Q	30-Day max Q	90-Day max Q
Arkansas	−83**	−83**	−78**	−68*	−63*
Canadian	−91**	−88**	−88**	−82**	−85**
Kansas	−19	−14	−1	30	41*
Lower Missouri	−66**	−64**	−61**	−43**	−24**
Upper Missouri	−56**	−54**	−50**	−41**	−27**
Pecos	−6	9	23	17	23
Red of the North	120**	123**	137**	137**	120**
Red of the South	−56**	−49**	−37*	−8	4
Republican	−75**	−73**	−73**	−66**	−65**
Wakarusa	−56**	−51**	−28	3	22
Mean decrease	56	60	52	51	53
Mean increase	120	66	80	52	42

* Significant difference between the two periods at the 5% level exists.
** Significant difference between the two periods at the 1% level exists.

Table 5
Timing of 1-day minimum and 1-day maximum discharge, where Q is discharge.

River	Pre-impact 1-day min Q	Post-impact 1-day min Q	# Days different	Pre-impact 1-day max Q	Post-impact 1-day max Q	# Days different
Arkansas	175	99	76	198	181	18
Canadian	316	193	123	208	236	28
Kansas	180	304	124	189	180	9
Lower Missouri	353	51	63	124	252	129
Upper Missouri	361	264	98	136	145	9
Pecos	184	311	127	182	241	59
Red of the North	213	269	56	124	129	5
Red of the South	232	291	59	183	171	12
Republican	291	241	50	158	189	31
Wakarusa	260	299	39	167	174	7
Mean			82			31

late October and early November, respectively. Following impoundment, Canadian River 1-day minimum discharge shifted from 12-November to 12-July. The date average of the 1-day maximum discharge shifted by 32 days, which was not as dramatically as the shift of the 1-day minimum discharge. The Lower Missouri River experienced the greatest temporal shift: from 4-May to 9-September, 129 days later.

4.4. Frequency and duration of high and low pulses

Among post-impoundment disturbance regimes, the overall average number of days with decreased low and high pulses was 78% and 83% of historical values, respectively (Table 6). The overall average decrease in the duration of low pulses and high pulses were 87% and 76%, respectively. Seven systems experienced a significant decrease in the number of high pulses, with the other two systems exhibiting a significant decrease in the number of high pulses, and the Red River of the North having a significant increase in the number of high pulse counts (Table 6). Six systems experienced a significant decrease in the duration of the high pulses, with the remaining three sites exhibiting a negative percent change in the duration, and the Red River of the North having a significant increase in the duration of high pulses. Seven systems exhibit a significant decrease in the number of low discharge pulse counts and four showed a significant decrease in the duration of low discharge pulses. All systems except for the Upper Missouri River show a decrease in the number and duration of low discharge pulses, the Upper Missouri River indicated a zero net alteration following

Table 6
Percent change in the means of pre and post-impact impact conditions for low and high pulse numbers and durations, where Q is discharge.

	% Change low pulse count	% Change low pulse length	% Change high pulse count	% Change high duration
Arkansas	−89**	−89	−64**	−79
Canadian	−87**	−95**	−80**	−39
Kansas	−84	−94	−87	−88**
Lower Missouri	−99	−100	−85**	−93**
Upper Missouri	0	0	−87*	−91
Pecos	−71**	−98	−95**	−93**
Red of the North	−53**	−30	96**	68*
Red of the South	−93**	−97**	−90**	−89**
Republican	−52*	−89**	−74**	−34**
Wakarusa	−77**	−95*	−88	−82**
Mean decrease	78	87	83	76
Mean increase	–	–	96	68

* Significant difference between the two periods at the 5% level exists.
** Significant difference between the two periods at the 1% level exists.

impoundment. In contrast, the Red River of the North experienced a significant increase in high pulse number and count.

4.5. Rate and frequency of discharge condition change

In six of 10 study systems, the number of hydrograph reversals changed significantly (Table 7). Among these six, five indicated an average increase of 45% in the number of reversals. The Republican River experienced a decrease in the percent discharge reversals. The percent change in rise rate significantly decreased in all the rivers except the Pecos River and the Red River of the North, with an overall average percent decrease in raise rates of 65%. Seven systems experienced a significant decrease in the percent change in fall rates, the Red River of the North exhibited a significant increase in the fall rate, and the two remaining systems did not have significant differences. The average decrease in the fall rate among study systems was 54%.

4.6. Overall hydrologic impact assessment

A comparative assessment of hydrologic regime alteration across sites is difficult because, as presented above, the impacts are numerous and variable across sites. Both sites on the Missouri River have the most altered hydrologic regime variables, with significantly different 1, 3, 7, 30 and 90-day minimum and maximum discharges and an average of 81 and 69 day shifts to the 1-day minimum and maximum mean annual discharges. In contrast, the Pecos River is not significantly altered in any of the minimum or maximum discharge averaging periods, reversals, or rise and fall rates. Principal components analysis was conducted to objectively evaluate the overall degree of impact across our study sites. Results indicate that the Missouri River sites are in fact the most altered, while the Kansas and Wakarusa Rivers are the least altered systems used in this analysis (Fig. 3).

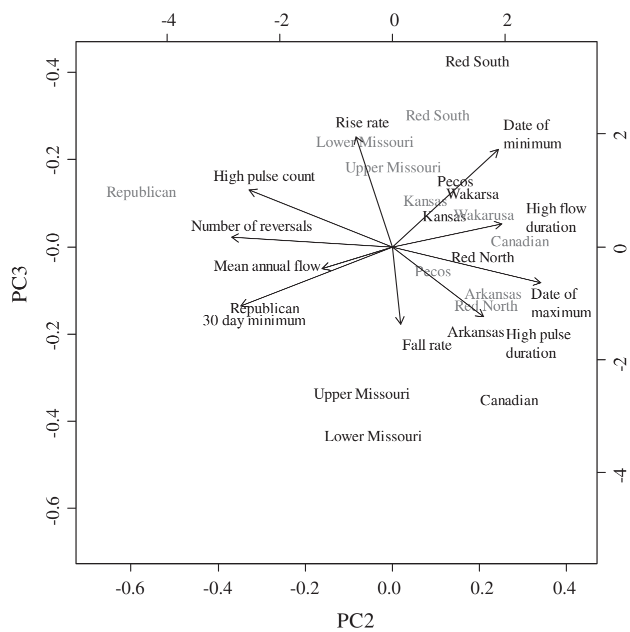

Fig. 3. Principal component analysis of the uncorrelated ($r > 0.8$) parameters calculated by IHA for pre (in gray) and post (in black) alteration of the systems used in this analysis.

Table 7
Percent change in the means of pre and post-impact impact conditions for hydrograph reversals and rise and fall rates, where Q is discharge.

River	% Change reversals	% Change, rise rate	% Change, fall rate
Arkansas	6	−85**	−84**
Canadian	49**	−95**	−94**
Kansas	6	−35**	−31**
Lower Missouri	58**	−75**	−64**
Upper Missouri	143**	−63**	−44**
Pecos	17	1	23
Red of the North	5	69**	58**
Red of the South	87**	−48**	−2
Republican	−10**	−74**	−74**
Wakarusa	36**	−46**	−40**
Mean decrease	10	65	54
Mean increase	45	35	41

*Significant difference between the two periods at the 5% level exists.
** Significant difference between the two periods at the 1% level exists.

5. Discussion

Our results indicate dramatic post-impoundment alteration of Great Plains river hydrologic regimes. Analyses supported the hypotheses that impoundment results in muted discharge magnitudes at both the high and low extremes, low discharge durations were reduced, and rise and fall rates increased. Our findings are consistent with other geographically extensive studies in that uniform, consistent trends in the hydrologic response of the rivers were not detected across the study region (Magilligan and Nislow, 2005), likely due to variable system-specific reservoir management objectives, land use changes, and climatic regimes. This was evident in the analysis of characteristic discharge, where distinctly different impacts were detected across systems. Mean annual discharge on the Canadian River decreased by 88%, which represents an additional decrease of 16% from that observed in a 1996 analysis of the system (Bonner and Wilde, 2000). Discharge decreases were also present at the Arkansas and Republican rivers. In contrast, mean annual discharge remained fairly stable post-impoundment at both systems on the Missouri as well as the Red River of the South, while the Kansas, Pecos, Wakarusa, and Red River of the North have all experienced increases in mean annual discharge. The Arkansas, Canadian, and Pecos Rivers are all subject to legal water compacts that dictate a minimum amount of acre-feet to be held or released, which aids in explaining some of the specific alterations of these systems. It is possible that reduced mean annual discharges may partially be the results of increased evaporation and/or infiltration and loss to groundwater. However, it is more likely that water withdrawals (both direct and through alluvial aquifer wells) and diversions for irrigation are responsible for these reductions in mean annual discharges as seen in this analysis.

Our results also demonstrated no uniform pattern of variation in monthly discharges across the study region. In some cases, such as the Missouri River, reservoirs are used to maintain downstream discharges for barge navigation, resulting in the impoundments storing water from March through July and then augmenting the discharge of the river August through February. The Red River of the North experiences its greatest increases in mean monthly discharges in February and March, attributable to seasonal shifts of warmer temperatures earlier in the year, to snowmelt and rain on frozen ground (Villarini et al., 2011), and to channelization and dam construction on tributary streams (Aadland et al., 2005). The Arkansas and Canadian Rivers both have a decrease in every month's mean discharges.

We did detect near-uniform patterns of change in the analyses of magnitudes of the mean maximum and minimum discharges, and low and high pulses, and reversals. All but three systems (Pecos, Red of the South, and Republican) experienced increases in 1, 3, 7 and 30 day minimum discharges, although only five of these were statistically significant. All but one system (the Red River of the North) experiences reductions in 1, 3 and 7 day maximum flow following impoundment; seven of these were statistically significant (Table 4). The impact on minimum and maximum discharges decreases as the temporal scale of analysis lengthens, particularly to the 30 and 90 day minimum and maximum discharge statistics, a finding which is consistent with results from similar studies of impounded hydrologic regimes (Magilligan and Nislow, 2005). Post-impoundment changes to the Julian calendar timing for 1-day minimum discharge varied considerably across systems, averaging more than a 3-month shift in timing across all systems and ranging from dramatic adjustments of over 120 days on the Kansas, Pecos and Canadian Rivers (Table 5). Alteration of the timing of 1-day maximum discharge was more muted, averaging about a 1 month shift with the exception of the 129 day shift at Lower Missouri River system. As with the 1-day maximum discharges, we detected an almost uniform overall decrease in low (with the exception of the Upper Missouri) and high (with the exception of the Red River of the North) pulses count and duration following impoundment (Table 6). The number of reversals increased at all study systems, other than the Republican River, where agricultural diversions may be the driver of this exception (Table 7) (Wu et al., 2009). Rise/fall rates declined at all systems other than the Pecos and the Red of the North. These relatively uniform alterations to the magnitudes of the mean maximum and minimum discharges, low and high pulses, and reversals are seen across the Great Plains region despite the varying hydrologic regimes and impoundment controls and are coincidental with changes observed at other gages evaluated in this region and throughout the continental United States (Magilligan and Nislow, 2005), suggesting that these particular metrics are relatively uniformly impacted by dams across geographical regions and reservoir management schemes.

Overall, it appears that both sites on the Missouri River have the most altered hydrologic regimes, with significantly different 1, 3, 7, 30 and 90-day minimum and maximum discharges and an average of 81 and 69 day shifts to the 1-day minimum and maximum mean annual discharges, respectively (Fig. 3). These rivers being the most altered is unsurprising since it is well known that the hydrologic regime of the Missouri River is highly controlled to support barge navigation and for flood prevention (e.g. Sparks et al., 1998), which is especially evident given the increased monthly discharges to support barge navigation through the winter and decreased monthly discharges in the spring during upstream snowmelt events. The Kansas and Wakarusa Rivers are the least altered systems used in this analysis (Fig. 3).

The consistent outlier in the study group was the Red River of the North, the one study system with no main-stem impoundment. This system has experienced significant changes to its hydrologic regime, but almost uniformly in opposing directions to the other study systems. Major differences include dramatically increased mean annual, mean monthly maximum daily discharges, increased high pulse counts, and increased rise and fall rates. While tributary dams could be responsible for some of the observed regime modifications, dams do not tend to increase total discharge (McClelland et al., 2004). Rather, the Red River of the North's uniquely altered hydrologic regime is likely the result of four factors: (1) the absence of a main-stem dam to control main-channel discharge patterns, (2) the widespread installation of agricultural drainage tile systems in the watershed, (3) increased precipitation over the study period, and (4) a decrease in surface storage in prairie potholes. Increases in both discharges and peak discharges are the product of expanded drainage tile systems, widespread channelization, and expansion of the stream network through ditching (e.g. Bluemle, 1997), which act to decrease surface and soil moisture storage, intercept groundwater recharge pathways, increase total runoff volume, greatly reduce lag time to peak discharge, increase peak discharge magnitudes, and generally produce more severe and frequent flooding than under natural watershed conditions (e.g. Poff et al., 1997; Melesse, 2004). During the late 19th and early 20th centuries, the prairie potholes in the Red River of the North's valley were completely drained (Dahl and Allord, 1996), with North Dakota losing 49% of its wetlands (Dahl, 1990). These anthropogenic watershed alterations may be compounded by the increasingly wet climate in the Great Plains region (Garbrecht et al., 2004; USGCRP, 2009). The lack of a main-stem dam limits the ability to moderate the anthropogenically enhanced river discharge and peak discharge magnitudes at the gaging site, producing the altered hydrologic regime parameters analyzed in this study.

6. Conclusion

This is the first study to systematically investigate impoundment-driven hydrologic alteration of rivers across the Great Plains physiographic region. The extent and magnitude of hydrologic alternations detailed by this study have tremendous implications for ecogeomorphology of Great Plains river systems. Exacerbating the well-known negative effects of physical fragmentation by dams, the dramatically altered hydrologic event frequencies, timing and magnitudes are likely contributing to the decline of native species. For example, the reduction of high pulse frequencies, durations and the shifting of peak discharge timings by more than a month in several cases is likely disrupting the reproductive timing for fish species in these systems. Similarly, reductions in low discharge pulse frequencies, durations and magnitudes and shifts in

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low discharge timing is likely disrupting the recruitment of riparian pioneer vegetation species. Hydrologic regime modifications detailed in this study are probably, in addition to sediment starvation, some of the primary drivers of the downstream geomorphic adjustments other studies have documented following impoundment construction. In particular, the elimination of the largest flood peaks and overall reduction in high pulse frequencies could be limiting rates of meander migration.

In light of the degree and permanency of the modifications brought by impoundment, it is difficult to arrive at management recommendations to mitigate these hydrologic regime alterations. Best management practices that use reservoir releases to approximate pre-impact hydrologic regimes are of course desirable (Poff et al., 1997; Pegg et al., 2003; Propst and Gido, 2004; Magilligan and Nislow, 2005), but adoption of these measures is often politically difficult and in many instances may not be possible given the need to protect developed floodplains, support navigation, and manage down-network discharges. Even modified reservoir management would not address the physical fragmentation caused the by physical barrier of a dam, and it is important to recognize that even the most ecologically minded reservoir management is unlikely to produce a fully functional naturalized hydrologic regime and certainly not a naturalized sediment regime (Schmidt et al., 1998). While some have suggested dams could be redesigned to release sediment consistent with natural sediment transport events (Ligon et al., 1995), even this would not address the detrimental effects on the unique life history requirements of pelagic-spawning fishes or otherwise migratory stream organisms (Agostinho et al., 2007). Furthermore, formerly active floodplains have been encroached upon by urban development that will prohibit restoration of historically representative large flood discharges.

Despite the limited options for hydrologic regime restoration, the timing and duration of high and low discharges can be managed as part of a long-term discharge prescription designed to improve ecosystem functioning (sensu Poff et al., 1997; Toth et al., 1998; Propst and Gido, 2004). In particular, the ecological needs of specific native assemblages of fish or plants can be targeted by adaptive ecosystem management efforts (Perkin and Bonner, 2011), and to our knowledge no attempts at this management technique exist within the Great Plains. As a beginning, rivers of the Great Plains would benefit from naturalizing discharge regimes by reducing discharges from the fall through winter, readjusting the timing of high pulses to that of the pre-impoundment, and reducing the number of hydrograph reversals, and moderating rise and fall rates (sensu Galat and Lipkin, 2000; Pegg et al., 2003). Conservation of Great Plains rivers should include protecting existing connectivity and natural discharge regimes while seeking opportunities to naturalize altered discharge regimes (Dynesius and Nilsso, 1994; Schaefer et al., 2003; Franssen et al., 2006).

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