Introduction

Assessing the ecological integrity of flowing waters necessitates characterizing the flow regime, because hydrological variability orchestrates the structure and function of fluvial hydrosystems (Vannote *et al.*, 1980; Karr & Dudley, 1981; Welcomme, 1985; Junk *et al.*, 1989; Poff & Ward, 1989; 1990; Heede & Rinne, 1990; Schlosser, 1991; Dynesius & Nilsson, 1994; Walker *et al.*, 1995; Petts & Amoros, 1996a; Poff, 1996; Stanford *et al.*, 1996; Lorenz *et al.*, 1997; Scott *et al.*, 1997). So paramount is the flow regime as an underpinning to ecological integrity that its protection or restoration has been accorded, "the natural flow paradigm" (Poff *et al.*, 1997; Richter *et al.*, 1997). The essence of the natural flow paradigm is that intra- and inter-annual variability in river flow, including magnitude, timing, duration, frequency, and rate of change are critical to sustaining the full native biodiversity and integrity of aquatic ecosystems (Walker *et al.*, 1995; Poff *et al.*, 1997; Richer *et al.*, 1997).

Alteration of the natural flow regime through impoundment and regulation for flood control, water supply, irrigation, navigation, and power generation has severely compromised the ecological health (*sensu* Karr, 1993) of most of the world's rivers. This is particularly pervasive for large rivers (average depth >1 m and requiring that measurements taken from a boat, Stalnaker *et al.*, 1989) and great rivers (hydrological units with watersheds >3200 km^2, Simon & Emory, 1995) in developed countries because of their long association with human activities (Ward & Stanford, 1983; Petts, 1984; Karr *et al.*, 1985; Welcomme, 1985; Davies & Walker, 1986; Dodge, 1989; Benke, 1990; Johnson *et al.*, 1995; Bravard & Petts, 1996; Haslam, 1997). Restoration and rehabilitation (see National Research Council, 1992; Gore & Shields, 1995 for the distinction between these terms) of the hydrological and ecological integrity of large rivers is therefore a major thrust of contemporary fluvial ecology (Gore, 1985; Poff & Ward, 1990; Sparks *et al.*, 1990; Boon *et al.*, 1992; National Research Council, 1992; Calow & Petts, 1992; Petts & Amoros, 1996b).

Assessment is a fundamental aspect of characterizing, conserving or recovering the ecological integrity of fluvial hydrosystems, and benchmarks or reference conditions are necessary to quantify what constitutes "healthy" or "integrity." If the goal of ecosystem restoration is to return the system to a semblance of its condition prior to disturbance (National Research Council, 1992), then defining a predisturbance or analog reference condition is a prerequisite to recovery. Reference conditions provide a benchmark to gage if restoration is moving in the right direction, tell us how far we have to go, and help identify if, or when, restoration is accomplished. Hughes (1995) gave six approaches for determining reference conditions. These include: regional reference sites, historical data, paleoecological data, experimental laboratory data, quantitative models, and best professional judgement. Assessing and restoring ecological integrity of large rivers precludes use of regional reference systems as there is only one Missouri or Colorado River. Additionally, biomonitoring, experimental studies, and quantitative models of large rivers are limited relative to wadeable streams due to their size and sampling difficulties (Johnson *et al.*, 1995; Reash, 1998). However, long-term hydrological records are often available for large rivers (Sparks, 1992).

An initial consideration to realize fluvial restoration is to restore or reregulate the natural flow regime (Bravard *et al.*, 1986; National Research Council, 1992; Gore & Shields, 1995; Stanford *et al.*, 1996; Poff *et al.*, 1997), since attempts to reestablish a river's biological integrity are doomed without recreating the underlying physical template. Schmidt *et al.* (1998) identified five management approaches to fluvial restoration of the Colorado River within the Grand Canyon that are applicable to most large rivers. Four of the five approaches (naturalized, simulated natural, substantially restored, and fully restored ecosystems) recognize to varying degrees the need to reestablish natural river flows. Bayley & Li (1992) encourage using a hydrological approach at a landscape perspective to provide a regional model for understanding community function, life-history patterns, and making inferences about riverine fishes. Most recently, numerous authors have recommended controlled dam releases or "managed flooding" to achieve reregulation of natural flows and their associated ecological processes in large rivers (Galat *et al.*, 1998; Michener & Haeuber, 1998; Molles *et al.*, 1998; Schmidt *et al.*, 1998; Sparks *et al.*, 1998; Toth *et al.*, 1998).

Our objective was to assess ecologically relevant components of the Missouri River's flow regime and their longitudinal variability before and after mainstem regulation. We use this information to provide initial guidelines for restoring a more natural hydrograph to enhance the ecological integrity of the river's imperiled biota.

Missouri River Hydrosystem

The Missouri River is the longest river in the conterminous United States. It extends 3768 km in a southeasterly direction across the midcontinent from the confluence of the Gallatin, Madison, and Jefferson rivers in southwest Montana to the Mississippi River, 24 km upstream from St. Louis, Missouri (Fig. 1). Its drainage basin encompasses about one-sixth of the conterminous United States (1,371,000 km^2) and includes parts of four physiographic provinces: 11% in the Rocky Mountains (western basin), 70% in the Great Plains (central basin), 17% in the Central

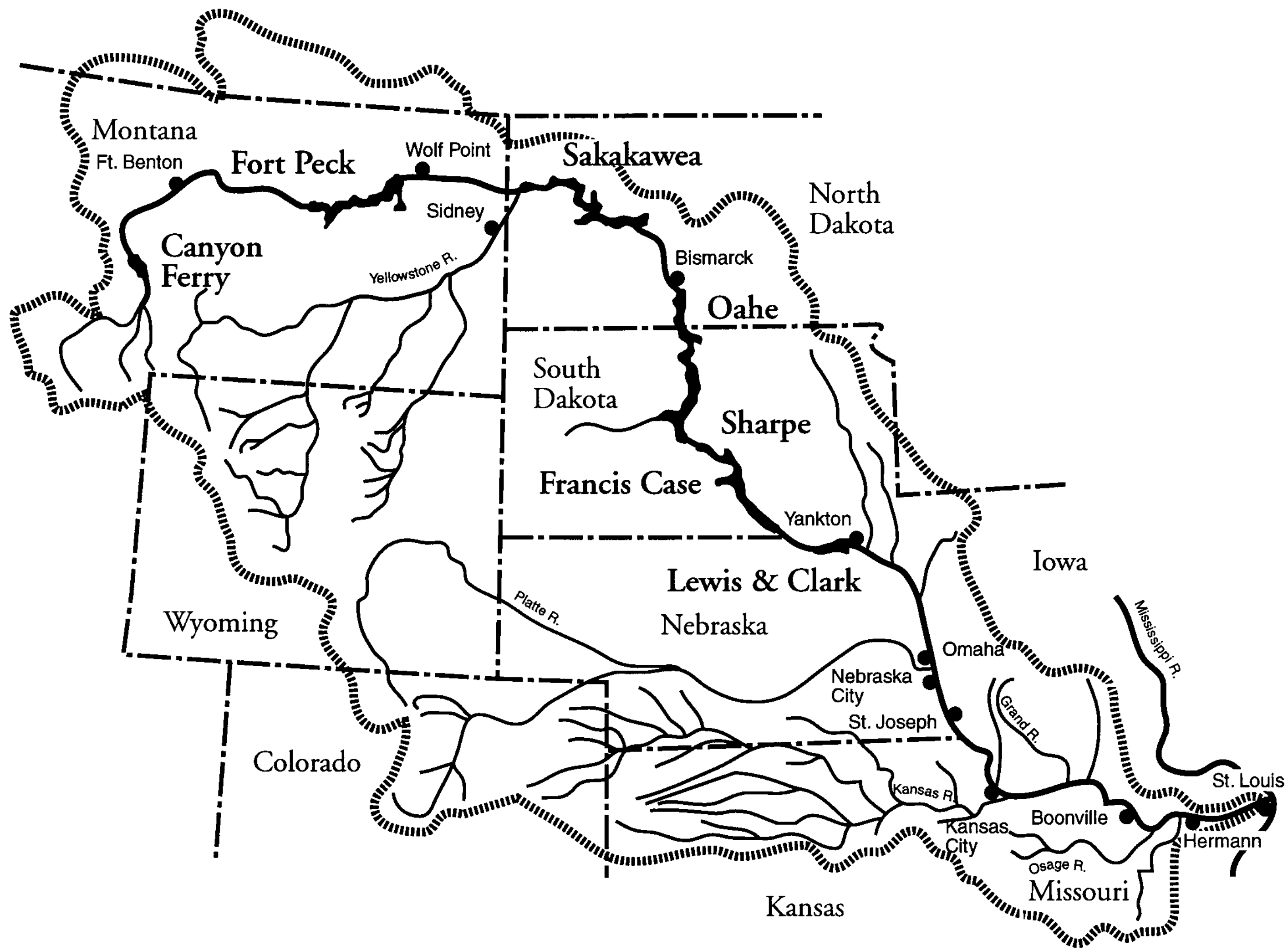

Fig. 1. Map of the Missouri River basin (thick broken line), the Missouri River and its major tributaries, mainstem reservoirs (names in **bold**), and locations of gaging stations where historical flow records were analyzed.

Lowlands (north, lower basin), and about 2% in the Interior Highlands (south, lower basin). The drainage basin is largely semi-arid, due to the dominance of the Great Plains. Average annual precipitation ranges from about 45 cm in the Great Plains, to 80 cm in the Rocky Mountains, and over 90 cm in the Interior Highlands (Hesse *et al.*, 1989). Consequently, discharge of the Missouri River is low relative to its length and area of its catchment. This is illustrated by contrasting the Missouri River with the Mississippi River near their confluence. Mean annual discharge per unit drainage area from 1951 to 1980 for the 3610 km long Missouri River at Hermann, Missouri, was about four times less (0.0016 m^3 sec^{-1} km^{-2}) than for the 1111 km long upper Mississippi River at Alton, Illinois (0.0065 m^3 sec^{-1} km^{-2}; data from Hedman & Jorgensen, 1990).

Development of the Missouri River was rapid following its exploration in 1804-1806 by the Lewis and Clark expedition as it became the first great highway for settlement and development of the American West. Details of its alterations are given by Hesse *et al.* (1989); Schmulbach *et al.* (1992); and Galat *et al.* (1996) and will be briefly summarized here. Public demands to improve navigation, irrigate the arid Great Plains, control devastating floods, and generate electricity began in earnest in the early 1900s. Today, this highly regulated river can be divided into three approximately equal length sections. The upper 1241 km has a complex of seven small mainstem dams and reservoirs (Canyon Ferry is the largest, Table 1), yet still represents a relatively "least-impacted" section. The 1233 km long middle or "inter-reservoir" section was impounded between 1937 and 1963 by a cascade of six large mainstem reservoirs (Table 1). Flows in the 1212 km lower section are regulated by upstream reservoirs. Channel–floodplain morphology in this section from Sioux City, Iowa (km 1178), to the mouth

Table 1. Characteristics of Missouri River mainstem reservoirs. Location of dam is kilometers upstream from Missouri River mouth. Sources: U.S. Bureau of Reclamation (1970), Schmulbach et al. (1992), U.S. Army Corps of Engineers (1996).

	Reservoir						
Characteristic	Canyon Ferry	Fort Peck	Sakakawea	Oahe	Sharpe	Francis Case	Lewis & Clark
Name of dam	Canyon Ferry	Fort Peck	Garrison	Oahe	Big Bend	Fort Randall	Gavins Point
Location of dam (km)	3688	2850	2236	1725	1589	1416	1305
Date reservoir filling initiated	Mar 1953	Nov 1937	Dec 1953	Aug 1958	Nov 1963	Jan 1953	Aug 1955
Year storage first available for flow regulation	1953	1940	1955	1962	1964	1953	1955
Total drainage area (10^3 km^2)	41.2	148.9	469.8	630.6	645.8	682.4	723.9
Length of full reservoir (km)	40	216	286	372	129	172	40
Gross volume (km^3)	2.53	23.05	29.38	28.54	2.29	6.78	0.61
Average annual discharge (km^3 yr^{-1})	4.75	7.78	21.28	22.80	19.37	13.76	15.55

was also highly altered by channelization, bank stabilization and levee construction to facilitate navigation and floodplain development (Schmulbach *et al.*, 1992; Galat *et al.*, 1996). This river segment will be referred to as the "channelized" section. Prior to flow regulation, the inter–reservoir and channelized sections were reported to exhibit a bimodal annual flow regime (Hesse *et al.*, 1989; Hesse & Mestl, 1993). There was a March "rise" derived from snow melt in the Great Plains and ice breakup on the main channel and major tributaries. A second, or June rise, was produced by runoff from snowmelt in the Rocky Mountains and rainfall throughout the basin. Reservoir releases are presently managed to maintain minimum target flows (700-1160 m^3 sec^{-1}) in the channelized section for the April-November navigation season and non-navigation season releases maintain minimum flows (170-650 m^3 sec^{-1}) for water quality, power production and flood control (Hesse *et al.*, 1989).

Impacts of impoundment, flow regulation, channelization, levees, and basin development on the system's ecology have been numerous and severe and are well documented (Funk & Robinson, 1974; Whitley & Campbell, 1974; Johnson *et al.*, 1976; Bragg & Tatschl, 1977; Hesse, 1987; 1996; Pflieger & Grace, 1987; Hesse *et al.*, 1988; 1989; 1993; Johnson, 1992; Schmulbach *et al.*, 1992; Galat *et al.*, 1996; 1998; Smith, 1996; Scott *et al.*, 1997). By 1990, 7 species of plants, 6 insects, 2 mussels, 16 fishes, 4 reptiles, 14 birds and 3 mammals were listed as endangered, threatened, or rare by state or federal agencies within the Missouri River basin (Whitmore & Keenlyne, 1990). The conservation organization American Rivers listed the Missouri River as North America's most endangered river in 1997 (American Rivers, 1997). Many of these sources have identified reestablishing the natural flow regime as a critical step in restoration of the basin's biota. Characterizing the magnitude, timing, frequency and duration of the pre–regulation flow regime along the Missouri River is an initial step in this process.

Range of Variation Approach

Methods for establishing instream flow requirements (Bovee, 1982) and defining habitat suitability (Terrell *et al.*, 1982) of individual species are well developed, but their application to the scale of large rivers and hundreds of species has been questioned (Bayley & Li, 1992) and they have been criticized as being overly simplistic and lacking an ecosystem perspective (see Richter *et al.*, 1997 for a review of their shortcomings). The Range of Variation Approach, or RVA, has recently been proposed by The Nature Conservancy (Richter *et al.*, 1997) as a method to assess and define river ecosystem management targets based on a comprehensive statistical characterization of ecologically relevant hydrologic parameters (Richter *et al.*, 1996).

The hydrological parameters used in the RVA comprise the "Indicators of Hydrologic Alteration," or IHA, method (Richter *et al.*, 1996). These parameters reflect five fundamental attributes of river flow that collectively have profound ecological significance: magnitude, timing, frequency, duration, and rate of change of discharge (Richter *et al.*, 1996; 1998; Poff *et al.*, 1997; Scott *et al.*, 1997). The IHA method calculates 32 ecologically relevant hydrologic parameters for each year of flow record (Table 2). Measures of central tendency (mean, median) and dispersion (range, standard deviation, percentiles, coefficient of variation, coefficient of dispersion) are used to characterize inter-annual variation before (reference period) versus after the system has been altered by human activities (Richter *et al.*, 1996). A fundamental concept of the RVA is that river flows should be managed so that post-regulation annual values of each IHA

Table 2. Summary of the 32 hydrologic parameters and their characteristics used in the Indicators of Hydrologic Alteration (IHA) method for the Missouri and lower Yellowstone rivers. Sources: Richter et al. (1996, 1998).

IHA statistics group	Regime characteristics	Hydrologic parameters (number)
Group 1: Magnitude of monthly discharge conditions	Magnitude, timing	Median discharge for each calendar month (12)
Group 2: Magnitude and duration of annual extreme discharge conditions	Magnitude, duration	Annual median discharge maxima and minima averaged over 1-day, 3-day, 7-day, 30-day, and 90-day intervals (10)
Group 3: Timing of annual extreme discharge conditions	Timing	Median Julian date of each annual (Jan–Dec) 1-day maximum and minimum discharge and median Julian date of each seasonal (Mar-Oct) 1-day minimum discharge (3)
Group 4: Frequency and duration of high and low flow pulses	Magnitude, frequency, duration	Median number and median duration of high and low discharge pulses each year (4)
Group 5: Rate and frequency of hydrograph changes	Frequency, rate of change	Mean of all positive and negative differences between consecutive daily discharge values and mean number of flow reversals (3)

parameter fall within the range of natural variation for that parameter as defined by an interannual measure of dispersion derived from the pre-regulation period. Specifically, post–regulation flows should be managed to fall within the targeted range of IHA values at the same frequency as the pre-regulation values (Richter *et al.*, 1997). For example, if the 25^{th} and 75^{th} pre-regulation percentiles are selected as RVA targets, then post-regulation values should fall within this range 50% of the time.

Methods

Richter *et al.* (1997) recommended six steps for setting, implementing, and refining flow management targets for a specific river or reaches within a river. We applied the first two steps to evaluate contemporary Missouri River hydrology relative to historical conditions. First, we assessed the natural range of flow variation using the 32 hydrological parameters calculated by the IHA method. Second, initial management targets were identified for these hydrological parameters using the RVA approach.

We characterized the range of discharge variation (Step 1) for the Missouri River using IHA before and after mainstem flow regulation, referred to hereafter as pre- and post–regulation, respectively. River-flow data were analyzed from gaging stations above (least–impacted), between (inter-reservoir), and below (channelized) the large mainstem reservoirs. Comparing hydrological parameters before and after flow regulation at stations above major reservoirs provides an estimate of the natural temporal variability between the two time periods and may also furnish a spatial reference to compare with downriver stations.

The IHA software uses daily flow data input by water year (WY, October 1-September 30). The U.S. Geological Survey (USGS) has been recording continuous daily discharge from a large number of gaging stations in the Missouri River basin since 1928. The first year of continuous daily flow records for most mainstem stations was water year 1929 (October 1928–September 1929). We searched the USGS's stream-flow records to locate mainstem Missouri River stations meeting three criteria: (1) a minimum of 13 years of continuous flow records both before and after reservoir construction; (2) location of stations within each of the least-impacted, inter-reservoir, and channelized river sections; (3) concentration of stations in river sections where input from major tributaries was highest.

Construction of the earliest dam on the mainstem Missouri (Ft. Peck) began in 1937 (Table 1). Hesse & Mestl (1993) reported that early operation of Ft. Peck Dam did not affect the natural hydrograph of the Missouri River at Bismarck, North Dakota (km 2115), Omaha, Nebraska (km 991), or Hermann, Missouri (km 158), until 1948. Thus, they defined the pre–regulation interval for the entire river as 1929-1948. Pflieger & Grace (1987) used the interval of 1926-1952 as before impoundment for their analysis of discharge data at Boonville, Missouri (km 317). We adopted Hesse & Mestl's (1993) WY 1929-1948 as the pre-regulation period for the entire river, but recognize that filling and operation of Ft. Peck Dam may have influenced river flow at gages between Ft. Peck and Bismarck (Wolf Point and Culbertson, Montana). Most mainstem reservoirs were constructed between 1953 and 1955 and the last dam (Big Bend) was completed in 1963 (Table 1). The six large mainstem dams commenced operation as a system in 1967 (Ferrell, 1993), so we defined the post-regulation period as WY

1967-1996. We did not include the 1949 to 1967 interval in our analysis because many of the mainstem reservoirs were filling during these years.

Twenty-four USGS gaging stations were identified along the mainstem Missouri with long-term flow records. These were reduced to 10 by deleting those with incomplete data (criterion 1: Toston, Helena, Wolf Creek, Ulm, Great Falls, Virgelle, Landusky, Ft. Peck Dam, and Culbertson, Montana; Pierre, South Dakota; Decatur and Rulo, Nebraska) or those that were redundant to nearby sites (Sioux City, Iowa; Waverly, Missouri).

To facilitate spatial comparisons, gaging station study sites are hereafter referred to by their location (km) upstream from the mouth of the Missouri River followed by a two-letter abbreviation of the station name. Least flow–impacted sites above the six large mainstem reservoirs are generally identified hereafter in **bold** typeface. Inter-reservoir stations and station 1297YT, just below the most downstream reservoir, Lewis & Clark Lake, are identified by normal type face, and stations in the lowermost flow-regulated and channelized section are distinguished by *italics*. Additionally, we added one tributary station to our analysis: Sidney, Montana (km 2592), on the lower mainstem Yellowstone River, 47 km upstream from its confluence with the Missouri. We included Sidney because the Yellowstone is the longest free–flowing, large river in the contiguous U.S. (Benke, 1990), has a greater discharge than the mainstem Missouri at their confluence (Table 3), and is recognized as a high-quality river (Benke, 1990; White & Bramblett, 1993). It provides a second least-impacted station to contrast with inter-reservoir and channelized sites. Neither stations **3336FB** nor **2592SN** are unimpacted by human activities, but can be considered little-impacted relative to other stations. Ft. Benton (**3336FB**) was included as a least-impacted station even though there are upstream reservoirs,

Table 3. Location (kilometers upstream from Missouri River mouth), drainage area, pre- (Oct 1929–Sep 1948) and post-flow (Oct 1967-Sep 1996) regulation mean annual discharge, and percent change in mean annual discharge from pre- to post-flow regulation at two stations on the Missouri and lower Yellowstone (**2592SN**) rivers upstream from large mainstem reservoirs (**bold**), three stations immediately below dams or between reservoirs, and six stations downstream from reservoirs in the channelized river (*italics*). Pre-flow regulation period is missing 1932-33 at km **2592SN**, 1929-1930 at km 1297YT, and 1929 at km *905*NC.

Name (USGS station number)	Station location (km) and ID	Drainage area (km^2)	Mean annual discharge (m^3 sec^{-1}) 1929-1948	1967-1996	Percent change
Fort Benton, MT (06090800)	**3336FB**	64,100	175.1	228.4	30.4
Wolf Point, MT (06177000)	2738WP	213,131	212.0	300.1	41.6
Sidney, MT YSR (06329500)	**2592SN**	178,977	332.6	358.4	7.8
Bismarck, ND (06342500)	2115BM	482,776	583.9	698.5	19.6
Yankton, SD (06467500)	1297YT	723,905	692.8	812.8	17.3
Omaha, NE (06610000)	*991OM*	846,306	771.5	1 012.2	31.2
Nebraska City, NE (06807000)	*905NC*	1,072,154	913.7	1 193.8	30.6
St. Joseph, MO (06818000)	*721SJ*	1,088,577	1007.4	1386.4	37.6
Kansas City, MO (06893000)	*589KC*	1,256,668	1240.9	1673.0	34.8
Boonville, MO (06909000)	*317BV*	1,299,403	1487.0	2020.4	35.9
Hermann, MO (06934500)	*158HM*	1,357,678	1955.6	2629.6	34.5

because Scott *et al.* (1997) considered it the least hydrologically altered alluvial portion of the upper Missouri River. Canyon Ferry reservoir's limited storage capacity, multiple-use operation of the dam, and few regulated upstream tributaries reduce its influence on peak flows (Scott *et al.*, 1997). Also, there are small reservoirs on tributaries to the Missouri and Yellowstone Rivers above both stations and significant water is withdrawn for irrigation from the Yellowstone River (White & Bramblett, 1993; Shields *et al.*, 1997).

Flow data were incomplete over the 50 year record for three of the 11 stations. One year of pre–regulation flows was absent from *905NC* (1929) and two years each at **2592SN** (1932–1933) and 1297YT (1929-1930).

Mainstem gaging stations provide point estimates of discharge, but they can represent reach conditions where tributary influence is minimal (Richter et al. 1998). For example, we assume hydrologic alterations in the mainstem Missouri River for the 121 km upstream from station 2115BM to Garrison dam are similar to those characterized at this site. The Knife River and three small streams are the only tributaries to the Missouri between km 2115 and km 2236 and their combined discharge is small (mean annual discharge 6.4 m^3 sec^{-1}, range 1.2-15.9 m^3 sec^{-1}, Harkness *et al.*, 1997). Likewise, flow patterns between 158HM and the confluence of the Missouri and Mississippi Rivers are defined by station *158HM* since there are no contributory streams of any magnitude along this reach. We make the same assumption for the Yellowstone River between Sidney, Montana (station **2592SN**), km 47 on the Yellowstone River, and its confluence with the Missouri.

Indicators of hydrologic alteration calculations

Specific methods used to compute each of the 32 IHA parameters, their measures of central tendency and dispersion and the RVA metrics are given in the IHA User's Manual (The Nature Conservancy, 1997) and are summarized in Richter *et al.* (1996; 1997). We outline selected methods specific to our analysis and for clarification.

We added an additional variable to the Group 3 statistics: Julian date (JD) of the "growing season" 1-day minimum flow where the growing season was defined as March 1–October 31 (JD 122-305). Minimum flows during this period are relevant to reproductive success of the federally endangered least tern (*Sterna antillarum*) and threatened piping plover (*Charadrius melodus*), which nest on exposed sand islands along the Missouri and its major tributaries (Smith, 1996; Bacon & Rotella, 1998). Timing of sand island exposure is also important to nesting success of softshell turtles (*Trionyx* spp., personal communication, R. Bodie, Dept. Biology, University of Missouri), as is exposure of mud flats to germination of annual moist-soil plants (Galat *et al.*, 1998). Additionally, most Missouri River fishes reproduce during the March-October interval (Galat *et al.* 1998) and shallow-water habitats are important nursery areas for many large-river fishes (Scott & Nielsen, 1989; Copp, 1991; Scheidegger & Bain, 1995; Poizat & Pont, 1996; Tibbs & Galat, 1998). It was not necessary to add a new variable to reflect the date of the growing season 1-day discharge maximum, because the maximum for the whole year always occurred between March and October at all stations.

Frequency and duration of high- and low-flow pulses are essential to the ecological integrity of large-floodplain rivers (Junk *et al.*, 1989; Sparks, 1995; Richter *et al.*, 1998). Specific high and low discharge thresholds can be user-defined in the IHA so that the number and duration of high and low pulses relative to these flows can be computed. Bankfull discharge is often used as an indicator of high pulses, since flows above this are considered channel forming and inundate much of the floodplain (Leopold *et al.*, 1964; Stalnaker *et al.*, 1989). However, there is a great deal of uncertainty and subjectivity in estimating bankfull conditions and different methods have been formulated to define bankfull discharge yielding a wide range of results (Johnson & Heil, 1996). Additionally, ecologically important water bodies periodically connected to the main channel are often inundated at flows below bankfull. Finally, channel geometry changes over years to decades, so it is not possible to select a single discharge to represent bankfull conditions at any station for 50 years. Richter *et al.* (1997) suggest a default definition of high pulses as >75th percentile of all pre-dam flows and low pulses as <25th percentile of all pre-dam flows; we have adopt this approach. However, we applied a somewhat more conservative criterion, defining the annual high-flow pulse at each station as the 75th percentile (%ile) daily discharge for the month with the highest pre-regulation monthly median discharge. Conversely, the low-discharge pulse was set as the 25th %ile daily discharge for the month with the lowest pre-regulation monthly median discharge.

Flow variation and predictability for the pre- and post-regulation periods are summarized in IHA output by two metrics: the annual coefficient of variation (Horwitz, 1978; Poff & Ward, 1989) and Colwell's (1974) measure of predictability for periodic phenomena (Resh *et al.*, 1988; Poff & Ward, 1989; Poff, 1996). Coefficients of variation (parametric, CV) and coefficients of dispersion (non-parametric, CD) are also calculated for the pre- and post-regulation periods for each hydrologic parameter. The CV for mean annual flow and individual hydrologic parameters was computed as: CV = SD/mean, and the CD for individual hydrologic parameters was computed as: CD = (75%ile-25%ile)/50%ile. Colwell's index of predictability (P) ranges from 0 (minimum predictability) to 1 (maximum predictability) and contains two additive components: constancy (C), and contingency (M). Constancy measures temporal variance and is maximum (C=1) if discharge is the same over the period of record. Contingency is a measure of periodicity and is minimum (M = 0) if there is no flow pattern over the period of record. Predictability and its components were computed in IHA for the Missouri River using all daily mean flows for the 1929-1948 interval before regulation and also for the 1967-1996 period after dams were operational.

Range of variability calculations

Once IHA parameter values are calculated (Step 1), the RVA recommends that flow management "targets" for each hydrologic parameter be based on a river management team's selected ranges of natural variation for that parameter (Step 2). In the absence of adequate ecological information to inform selection of these targets, Richter *et al.* (1997) recommend using ±1 standard deviation (SD) of pre-development hydrologic parameters as initial targets; we follow this general approach. Using this approach, river managers would strive to maintain 67% of all annual values for each IHA parameter within the ±1SD range. However, hydrologic data are often skewed so that ±1 SD falls outside the range of observed values. This occurred for various parameters within Groups 1-4 of the IHA statistics for the Missouri River data set. Consequently, we report median (50th%ile) values rather than means for parameters within Groups 1-4 and use the 25th and 75th%iles as our flow management targets rather than ±1 SD. The mean and ±1 SD were used for Group 5 parameters (rise rate, fall rate, and number of flow reversals). Reporting individual medians or means and their variability for 32 hydrologic parameters for 11 stations, before and after flow regulation, would be unwieldy. Therefore, we summarize each IHA parameter in the main Report as the percent change in medians or means and CDs or CVs from the pre-regulation to post regulation period: %CHG = [(post-regulation value) - (pre-regulation value)]/ (pre-regulation value) * 100. Pre- and post-regulation medians or means for the five IHA groups are provided in Appendix A. Complete IHA and RVA parametric and non-parametric outputs for each station in $ft^3\ sec^{-1}$ (CFS) are included in Appendix B.

Using measures of dispersion based upon pre-regulation data as flow "targets" is one of the valuable features of the RVA. It evaluates if post-regulation hydrologic conditions occur at the same frequency as before regulation (Richter *et al.*, 1998). Pre-regulation annual values for hydrologic parameters fall within the 25th-75th%ile values 50% of the time and within $\pm$1 SD about 67% of the time. Thus, only one-half to two-thirds of annual values for post-regulation IHA parameters are expected to fall within the pre-development flow regime for post-regulation observations to meet target criteria. The degree to which the selected pre-regulation RVA measure of dispersion is not attained is an estimate of "hydrologic alteration" (Richter *et al.*, 1998). We follow Richter *et al's*. (1998) example and report the percent of hydrologic alteration as: %HA = ((Observed - Expected)/Expected) * 100. "Observed" is the count of post-regulation years the hydrologic parameter was observed within the pre-regulation 25-75th%iles or $\pm$1 SD of the pre-regulation mean. "Expected" is the count of post-regulation years the hydrologic parameter is expected within the 25-75th%iles or $\pm$1 SD of the mean, which by definition, is 50 or 67%, respectively. Thus, %HA = 0, when the observed frequency of post-regulation years falling within the pre-regulation target range (25-75th%iles or $\pm$1 SD) is the same as expected during the pre-regulation period. When %HA >0, this indicates that post-regulation annual parameter values fell within the RVA target window *more* often than expected, while %HA <0 for a post-regulation parameter indicates annual values fell within the RVA target window *less* often than expected. We further abstract hydrologic alteration among stations by dividing %HA values (absolute) into four classes of equal range: 0 = 0-25%, represents low alteration; 1= 26-50%, represents moderate alteration; 3 = 51-75%, represents a high alteration; and, 4 = 76-100% represents an extreme degree of alteration. These ranks were first averaged over the hydrologic indicators within each of the five IHA groups (Table 2) and then the group means were averaged to yield an index of overall hydrologic alteration for each station. Caution is advised not to overinterpret this summary index as combining offsetting variables might yield similar overall %HAs among stations which exhibit widely different causes of impairment. Management actions should rely on consideration of each of the 32 individual indicators.

Results

Mean annual discharge (1929-1996) increased gradually from **3336FB** to *991OM*, as few large tributaries contribute flow in this section; the Yellowstone River (confluence with Missouri River at km 2545) being the largest (Fig. 2). Down river from *991OM* flow increased more steeply with the input of several tributaries (Platte, km 957; Kansas, km 591; Grand, km 402; Chariton, km 366; Osage, km 209, and; Gasconade, km 168). Although the lower 991 km of river drains about 38% of the total Missouri River catchment, it contributed 61% of the 50 year mean annual discharge at 158HM.

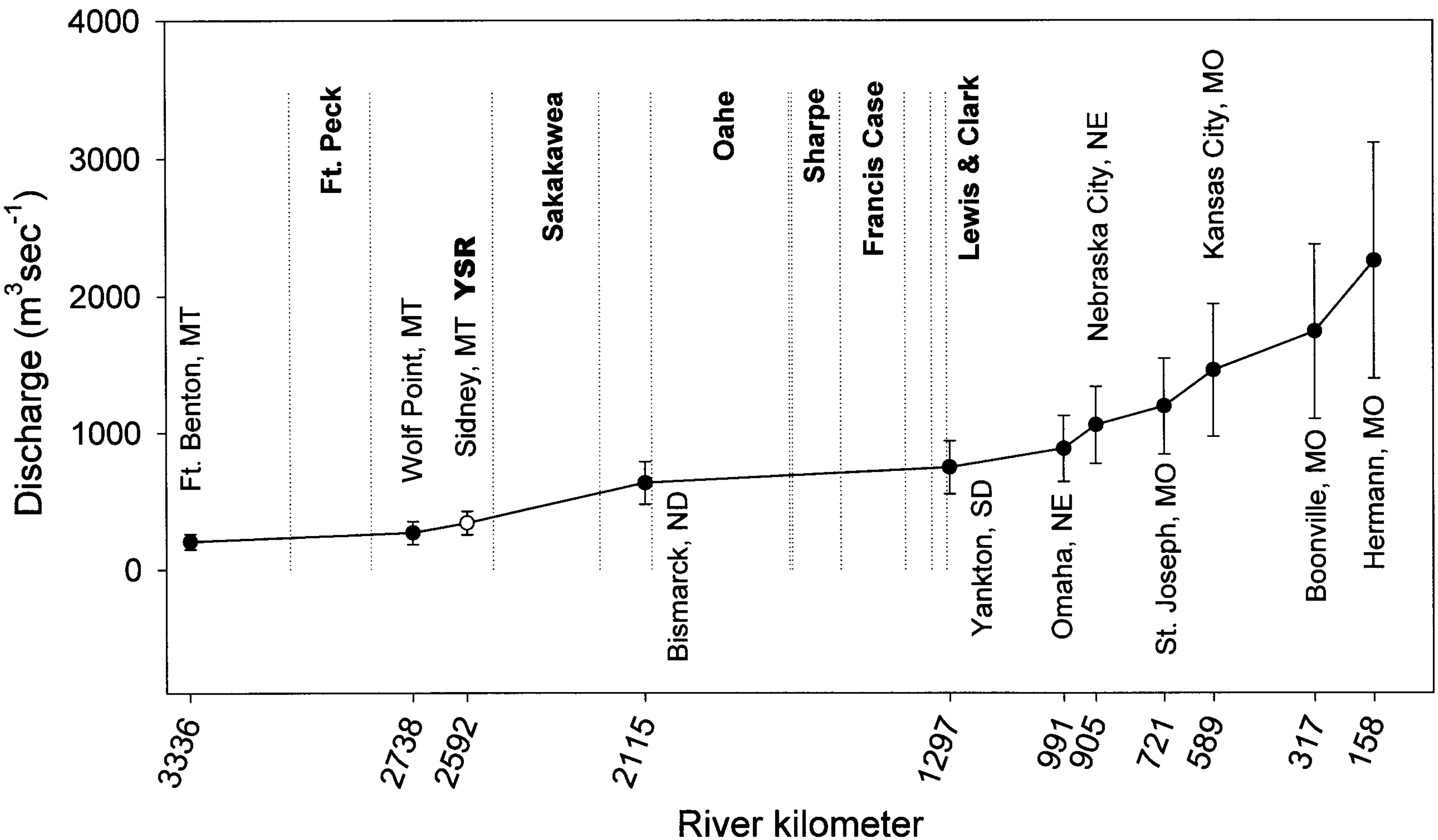

Fig. 2. Mean annual discharge, ±1 standard error, for 11 stations along the Missouri and lower Yellowstone (YSR) rivers for water years 1929 through 1996. Vertical dotted lines show locations of large mainstem reservoirs (names in bold type). River kilometer is location of stations above Missouri River mouth.

Mean annual discharge for the 30 year post-regulation period was higher at all stations than for the 20 years before mainstem dams operated as a complex (Table 3). This increase in discharge was <10% at **2592SN** of the unimpounded lower Yellowstone River, but about 30% higher at **3336FB**. The discharge increase at the six channelized stations on the lower Missouri River was similar to that at **3336FB**, ranging from about 30 to 38%. The greatest increase in post-regulation discharge was observed at 2738WP, below Ft. Peck Dam. This was an artifact of including reservoir filling in the 1929-1948 pre-regulation interval. Post-regulation discharge increases that were smaller than the catchment average were observed at the other two inter–reservoir stations, 2115BM and 1297YT (Table 3). Mean annual CV for discharge ranged from 0.78 to 1.07 for the 1929-1948 interval and decreased at all stations for the 1967-1996 post–regulation interval (Table 4). The decrease in flow variability between the two time intervals was smallest at the two upper basin, least–impacted stations (**3336FB** and **2592SN**) and also at the two stations furthest downriver from dams (*317BV* and *158HM*). Post-regulation flow variability decreased most after impoundment below the two large upper-basin reservoirs (2738WP, 2115BM) and the reduction in CV became progressively smaller downriver. Inter–annual flow predictability at all stations was moderately high and ranges for the pre- (0.44 to 0.68) and post–regulation (0.55 to 0.73) periods were small. Predictability increased between the two time intervals, although minimally at **3336FB** and **2592SN**. The increase in predictability from pre- to post-regulation was progressively less moving downriver, so that by *158HM* the difference observed between pre- and post-dam periods was within the range recorded at the upper basin least-impacted stations. Flows were relatively uniform among years at all stations, as constancy was the predominant component of predictability (C/P ranged from

Table 4. Mean annual coefficient of variation, predictability, constancy, and contingency for pre- (Sep 1929-Oct 1948) and post-flow (Sep 1967-Oct 1996) regulation discharge at two stations on the Missouri and lower Yellowstone (YSR) rivers upstream from large mainstem reservoirs (**bold**), three stations immediately below dams or between reservoirs, and six stations downstream from reservoirs in the channelized river (*italics*).

	Coefficient of variation		Predictability		Constancy		Contingency	
Station	Pre	Post	Pre	Post	Pre	Post	Pre	Post
3336FB	0.82	0.59	0.68	0.69	0.54	0.60	0.14	0.09
2738WP	0.85	0.38	0.44	0.68	0.35	0.63	0.09	0.05
2592SN YSR	1.07	0.87	0.59	0.64	0.37	0.47	0.22	0.17
2115BM	0.89	0.34	0.58	0.68	0.39	0.64	0.19	0.04
1297YT	0.91	0.41	0.59	0.73	0.39	0.59	0.20	0.14
991OM	0.86	0.38	0.58	0.69	0.38	0.59	0.20	0.10
905NC	0.78	0.41	0.59	0.67	0.41	0.58	0.18	0.09
721SJ	0.79	0.48	0.58	0.65	0.40	0.56	0.18	0.09
589KC	0.85	0.58	0.56	0.63	0.39	0.53	0.17	0.10
317BV	0.93	0.69	0.54	0.61	0.39	0.51	0.15	0.10
158HM	0.95	0.70	0.52	0.55	0.40	0.48	0.12	0.07

63 to 80% during pre–regulation and 73 to 93% for post-regulation). Constancy of flow increased from pre- to post-impoundment (range of increase: 11-80%), while contingency was low overall (range: 0.04–0.22) and decreased (-23 to -79%) throughout the basin following flow regulation. These results indicate low inter-annual discharge periodicity that decreased further in the post-regulation period.

Magnitude of monthly discharge

The general pattern of mean monthly discharge at all stations before mainstem impoundments were operational was an extended period of low flow from August through February (Fig. 3, top). Mean discharge increased beginning in March at most stations, showed a small peak in April between 2115BM and *589KC*, and was highest during June along the river continuum. The annual flood pulse was unimodal at least-impacted site **3336FB** (June peak), weakly bimodal at 2738WP and 2115BM, (April, June peaks), strongly bimodal at **2592SN** (March, June peaks) and also at 1297YT, *991OM,* and *905NC,* but with April and June peaks. The bimodal flood-pulse pattern weakened down river from *991OM,* gradually becoming nearly unimodal again at the lowermost station (*158HM*). A small mean November flow pulse was also observed before flow regulation at the two lowermost stations (*317BV*, *158HM*). The absence of a distinct flood pulse at 2738WP relative to **3336FB** and **2592SN** (Fig. 3, top) again appeared to be a result of filling Ft. Peck reservoir in the "pre–impoundment period."

The general seasonal pattern of post-regulation flows was a smoothing of mean monthly discharge by an increase in late-summer through early-winter low flows and a reduction in spring and early-summer high flows (Fig. 3, bottom). This change was absent at least-regulated

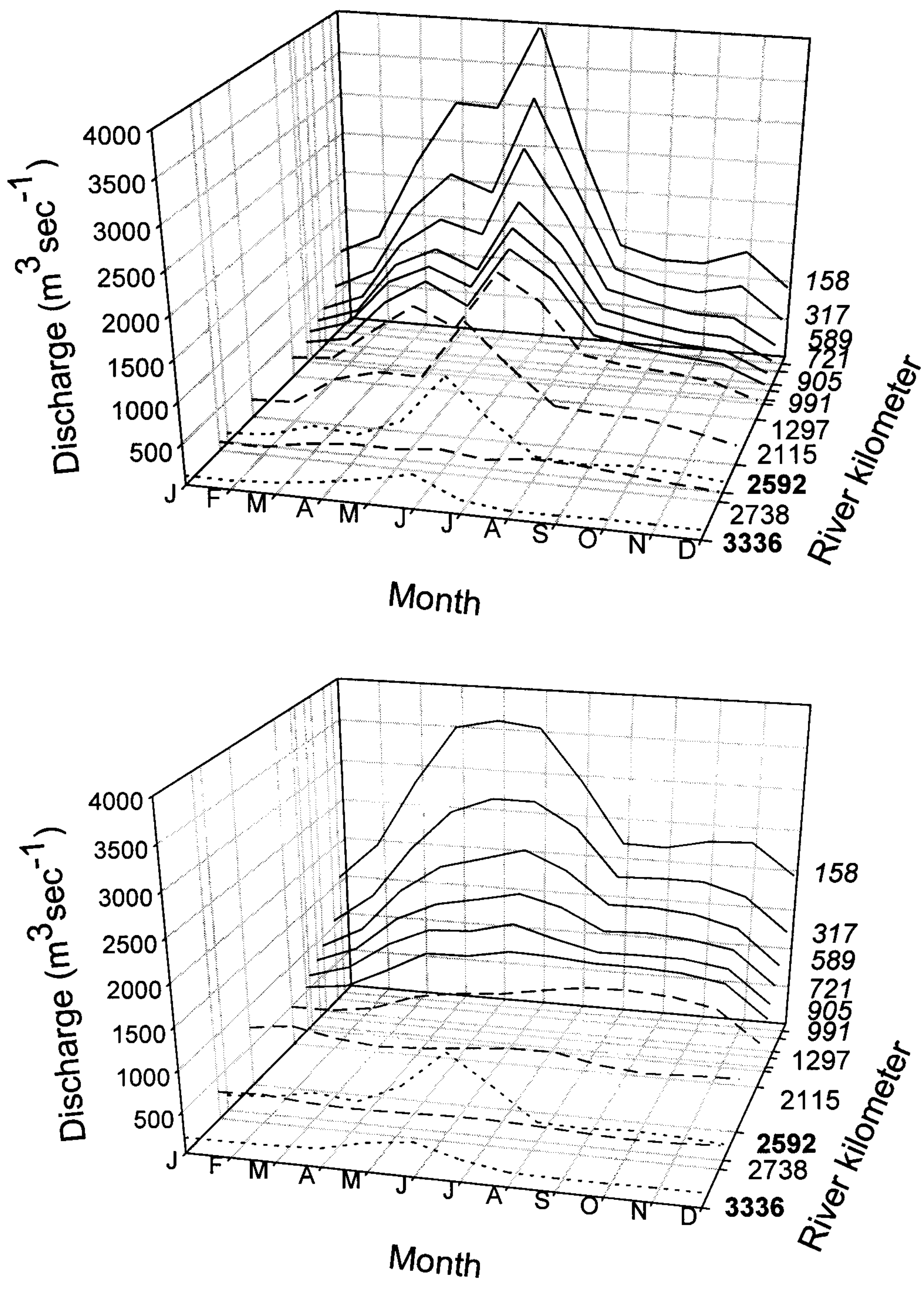

Fig. 3. Mean monthly discharge before (top, Oct 1929-Sep 1948) and after (bottom, Oct 1967–Sep 1996) flow regulation along the mainstem Missouri and lower Yellowstone rivers. Stations above large mainstem reservoirs are indicated by dotted lines, those between and immediately below reservoirs by dashed lines, and those below reservoirs in the channelized Missouri River are identified by solid lines. River kilometer is distance above the Missouri River mouth. Station 2592 (Sidney, MT) is on the undammed Lower Yellowstone River.

stations (**3336FB**, **2592SN**), most pronounced at inter-reservoir and upper channelized sites, and less prevalent at lower channelized river sites (*589KC-158HM*). Once the mainstem dams became operational, the naturally bimodal flood-pulse became unimodal at all sites below reservoirs and the small fall pulse at sites *317BV* and 158HM disappeared because of constantly high summer-autumn reservoir water releases.

Contrasting 1967-1996 with the 1929-1948 pre-dam interval shows that median monthly discharge increased throughout the Missouri and lower Yellowstone Rivers from late summer through winter (August-February). August through February median monthly discharges at most stations were outside the pre-regulation 25-75th percentile flow intervals more than expected for post-regulation years (as indicated by HA values mostly <0 in Table 5). Flow variability (% change in CD) was lower following impoundment for most months and gaging stations (Table 5). Median monthly discharge decreased at many inter-reservoir and upper channelized-river stations in June and July. April and July %HA was often positive following flow regulation, indicating that more years were within the 25-75th pre-regulation %iles than expected for many stations, but there was no consistent trend in %HA for March, May or June (Table 5).

Median flows for the peak discharge month of June decreased 16% at least-impacted station **2592SN** between the two time intervals, the CD increased by 50%, and 27% fewer years were within the 1967-1996 target window for June discharge (Fig. 4). In contrast, median June discharge increased 37% at **3336FB**, the CD was less, and 20% fewer years than expected were within the 1929 to 1948 25-75th%iles. Decreases in June discharge attributed to flow regulation were highest at inter-reservoir sites 2115BM and 1297YT and became progressively less moving downriver through the channelized reach (Fig. 4). There were no, or negligible, decreases in

Table 5. Percent change in median, coefficient of dispersion, and hydrologic alteration of monthly discharge between pre- (Oct 1929-Sep 1948) and post-flow regulation (Oct 1967-Sep 1996) periods along the Missouri and lower Yellowstone (**2592SN**) rivers. Station locations are kilometres above Missouri River mouth. Station numbers in **bold** type are the least flow-impacted, those in regular type are inter-reservoir or immediately below reservoirs, and those in *italics* are below reservoirs in the channelized river. See text for how hydrologic alteration was calculated.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Median												
3336FB	77	72	45	21	21	37	105	85	51	36	34	48
2738WP	285	366	90	-12	30	-6	64	47	100	77	92	230
2592SN	49	68	-12	24	11	-16	-7	17	42	35	26	70
2115BM	314	272	18	9	-6	-54	-21	43	43	56	118	201
1297YT	128	97	-15	5	19	-43	-18	62	88	157	143	126
991OM	106	108	13	14	31	-27	-7	65	83	120	128	165
905NC	63	52	14	23	32	-19	-15	55	59	67	97	128
721SJ	71	61	22	32	47	-7	2	63	90	75	103	123
589KC	55	50	10	22	44	-3	-4	68	88	98	95	129
317BV	70	63	0	27	50	-4	-6	64	79	80	107	117
158HM	47	81	19	37	48	0	5	55	67	76	101	93
Coefficient of dispersion (CD)												
3336FB	-61	-29	18	-54	4	-17	10	63	15	46	2	-50
2738WP	-84	-81	-55	28	-56	-48	-52	-68	-75	-50	-27	-81
2592SN	-25	17	-6	-28	-4	50	-21	-19	-39	-26	25	-44
2115BM	-67	-56	-52	-60	-36	9	-49	-47	-49	-12	-8	-48
1297YT	-25	-51	-69	-79	-63	-55	-72	-17	-48	-65	-37	46
991OM	-8	-35	-38	-67	-47	-43	-45	-23	-52	-53	-12	54
905NC	17	-17	73	-44	-32	-28	-27	-35	-41	-36	-9	45
721SJ	40	-8	27	-46	-19	-46	-46	-23	-48	-53	-14	-7
589KC	25	32	44	-9	-20	-60	-29	-27	-10	-44	-39	-15
317BV	-15	45	25	2	-42	-63	-15	-27	20	-24	-37	-17
158HM	-6	8	93	-1	-25	-45	-10	-34	18	-19	0	-20
Hydrologic alteration (HA)												
3336FB	-87	-93	-47	67	-53	-20	-27	-80	-67	-33	-40	-73
2738WP	-100	-100	-53	33	53	60	-7	93	87	27	-60	-100
2592SN	-93	-87	40	27	-7	-27	20	0	7	-13	-47	-53
2115BM	-100	-100	27	33	13	-60	60	-47	0	-13	-47	-100
1297YT	-100	-80	60	67	47	-80	87	-87	-87	-87	-87	-100
991OM	-100	-87	60	87	0	-13	80	-100	-100	-100	-73	-100
905NC	-93	-47	-40	33	7	0	73	-87	-100	-100	-73	-93
721SJ	-93	-40	-27	47	-13	27	67	-80	-87	-100	-80	-87
589KC	-80	-47	-20	20	-7	40	60	-60	-87	-100	-73	-80
317BV	-67	-53	-13	33	13	40	40	-67	-87	-73	-67	-73
158HM	-13	-33	-47	7	7	47	40	-67	-67	-67	-53	-53

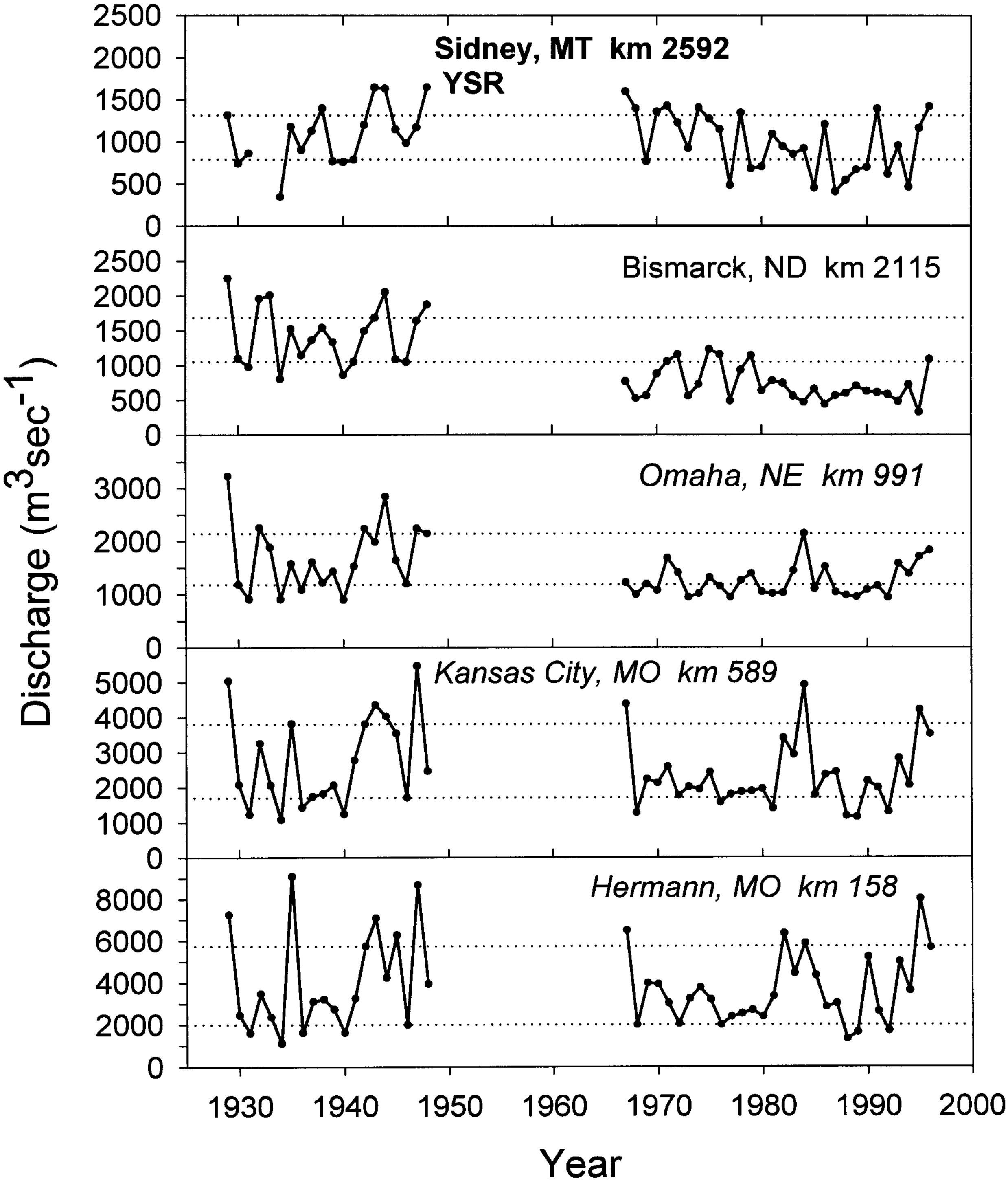

Fig. 4. June median discharge at five stations along the Missouri and lower Yellowstone rivers (YSR) before (1929-1948) and after (1967-1996) flow regulation. No flow records were available for Sidney, MT, during 1932-33. The horizontal lines are the 25th (lower) and 75th (upper) percentiles for the pre-regulation interval and define a target range of acceptable hydrologic variability for post-regulation years. Numbers within panels identify station locations in kilometers above Missouri River mouth.

median June flows following impoundment at channelized river stations *721SJ, 589KC*, *317BV*, and *158HM*, but variability in June discharge did decrease (Fig. 4, Table 5). Fewer post–regulation years than expected were within the pre-regulation 25-75th%iles for June discharge at stations above *905NC* (except for below Ft. Peck Dam, 2738WP). The number of years where June discharge was outside the pre-regulation target window generally decreased downriver until there was no difference between the two time intervals at *905NC* (Fig. 4). Below *905NC*, a higher number of post-regulation years were within the pre-regulation June flow 25th–75th%iles than expected.

Magnitude and duration of discharge extremes

Patterns of annual discharge maxima and minima were similar among the 1-, 3-, 7-, 30-, and 90–day averaging windows so we report only the 1-, 7-, and 30-day results (Table 6) and illustrate trends in 7-day highs and lows for representative stations (Figs. 5 and 6). Summary statistics for the five time-averaging windows are in Appendix A, Table A2. Post-regulation median discharge maxima for 1-, 7-, and 30-day intervals were between 12 and 23% lower than before regulation at **2592SN** on the Yellowstone River, but about 30% higher at the least–regulated Missouri River station (**3336FB**). Medians of the annual maximum flows for the three averaging durations were nearly all less after regulation for inter-reservoir and channelized river stations 2738WP to *905NC*; station *721SJ* was transitional, and maximum flows increased from *589KC* downstream to the Missouri's confluence with the Mississippi. Post-impoundment variability of annual maximum flows decreased at **3336FB**, all inter-reservoir stations and the uppermost channelized river site (*991OM*); it increased at stations *905NC* and *721SJ* in the

Table 6. Percent change in nonparametric (median, coefficient of dispersion) and parametric (mean, coefficient of variation) statistics, and hydrologic alteration for five groups of hydrologic variables between pre- (Oct 1929-Sep 1948) and post-flow regulation (Oct 1967-Sep 1996) periods along the Missouri and lower Yellowstone (**2592SN**) rivers. All hydrologic parameters are summarized by nonparametric statistics except rise rate, fall rate, and number of reversals which are summarized by parametric statistics. Refer to Table 3 for station locations in relation to reservoirs. See Table 2 for definitions of hydrologic terms and text for how hydrologic alteration was calculated. JD = Julian date.

	Group 2 - Magnitude & duration of annual discharge conditions						Group 3 - Timing of annual extreme discharge extremes			Group 4 - Frequency & duration of high & low pulses				Group 5 - Rate & of hydrograph changes		
	Max			Min			JD annual		JD Mar-Oct	High pulse		Low pulse				
Station	1d	7d	30d	1d	7d	30d	Max	Min	Min	Count	Dur.	Count	Dur.	Rise rate	Fall rate	No. flow reversals
Median/mean																
3336FB	30	27	33	69	41	51	3	34	14	100	-21	-11	-77	-15	-17	-6
2738WP	-27	-28	-21	370	346	176	-31	-38	22	50	-48	-40	-72	-39	-27	51
2592SN	-12	-23	-12	126	102	51	4	8	-3	0	24	-17	-45	-33	-34	-4
2115BM	-61	-52	-41	256	260	177	-38	-55	5	25	-41	0	-74	-62	-48	145
1297YT	-59	-52	-34	144	148	149	95	48	-48	-50	-3	-75	76	-76	-62	56
991OM	-36	-40	-17	207	204	157	12	13	-51	-33	-42	-75	156	-53	-44	40
905NC	-21	-29	-12	174	186	124	1	12	-29	-17	-31	-78	101	-42	-40	30
721SJ	6	-8	-1	212	250	140	3	9	-28	40	5	-63	46	-13	-17	24
589KC	15	1	5	163	179	126	-1	7	-30	0	17	-63	16	-6	-11	19
317BV	49	30	25	117	136	97	4	5	-18	50	19	-56	-34	13	11	16
158HM	21	38	53	91	94	100	-1	7	-21	60	20	-33	-34	14	13	14
Coefficient of dispersion/coefficient of variation (CD/CV)																
3336FB	-20	-28	-11	-48	-8	-5	94	-27	48	25	68	-39	152	37	35	-21
2738WP	-5	-27	-40	-50	-53	-39	-10	406	49	50	168	483	38	-23	0	-22
2592SN	-25	5	29	48	18	-2	-15	159	25	33	2	100	0	-35	-39	-26
2115BM	-51	-47	-45	-38	-27	8	71	144	212	260	37	100	-31	-9	14	-30
1297YT	-16	-22	-14	28	-12	-46	-12	187	70	167	125	33	97	18	58	75

Table 6 (continued).

Station	Group 2 - Magnitude & duration of annual discharge conditions						Group 3 - Timing of annual extreme discharge extremes			Group 4 - Frequency & duration of high & low pulses				Group 5 - Rate & of hydrograph changes		
	Max			Min			JD annual		JD Mar-Oct	High pulse		Low pulse				
	1d	7d	30d	1d	7d	30d	Max	Min	Min	Count	Dur.	Count	Dur.	Rise rate	Fall rate	No. flow reversals
Coefficient of dispersion/coefficient of variation (continued)																
991OM	-1	-13	-15	30	2	7	7	60	84	250	315	60	314	-4	-11	-28
905NC	39	52	19	15	-4	10	14	-14	106	140	292	200	133	16	18	-7
721SJ	25	50	5	-28	-45	-3	20	17	197	25	42	33	107	34	7	-8
589KC	-36	-16	-8	16	-18	-15	149	-14	252	25	-58	100	81	15	9	10
317BV	-67	-50	-32	17	11	76	53	0	140	17	-49	80	43	-10	-3	-4
158HM	-46	-47	-51	34	46	1	168	125	115	-22	-45	-200	60	-20	-20	-6
Hydrologic alteration (HA)																
3336FB	-7	7	-20	-53	-73	-87	-53	-40	-60	-60	-33	47	-40	-35	-35	15
2738WP	-40	-40	-33	-100	-100	-100	13	80	-67	-27	-47	-80	-53	-30	-15	-70
2592SN	27	13	-7	-87	-67	-73	-20	13	-13	13	27	-13	-33	15	5	20
2115BM	-93	-93	-40	-100	-100	-100	-40	80	-87	-73	7	-27	-67	-85	-80	-100
1297YT	-100	-100	-47	-67	-80	-87	-93	-73	-93	-33	-53	-67	-73	-100	-95	-95
991OM	-73	-60	7	-87	-100	-100	-40	-60	-47	-40	-73	-60	-73	-80	-75	-100
905NC	-47	-40	0	-87	-100	-100	-27	-67	-67	-60	-73	-87	-60	-50	-55	-90
721SJ	-33	-27	0	-73	-87	-100	-20	-13	-67	-20	-40	-53	-53	-20	0	-80
589KC	47	33	20	-73	-80	-87	-47	47	-80	-20	47	-67	-47	0	5	-75
317BV	67	53	20	-93	-100	-100	-7	67	-73	-47	27	-33	-7	10	10	-35
158HM	60	53	47	-73	-73	-73	-20	73	-40	-27	53	-53	-33	15	20	-25

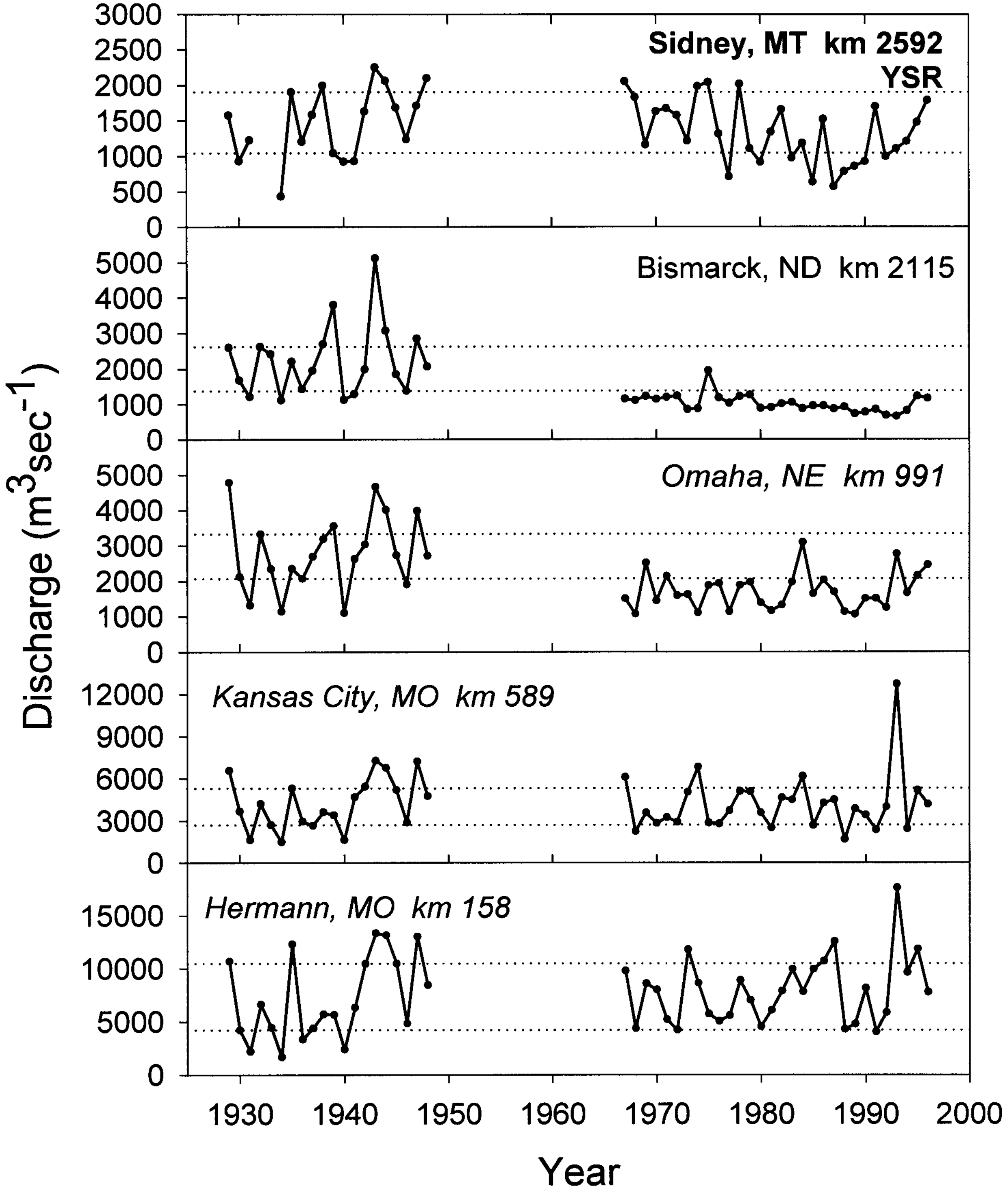

Fig. 5. Annual maximum 7-day median discharge at five stations along the Missouri and lower Yellowstone rivers (YSR) before (1929-1948) and after (1967-1996) flow regulation. The horizontal lines identify a target range of acceptable variability for the post-regulation period. Refer to Fig. 4 for further explanation.

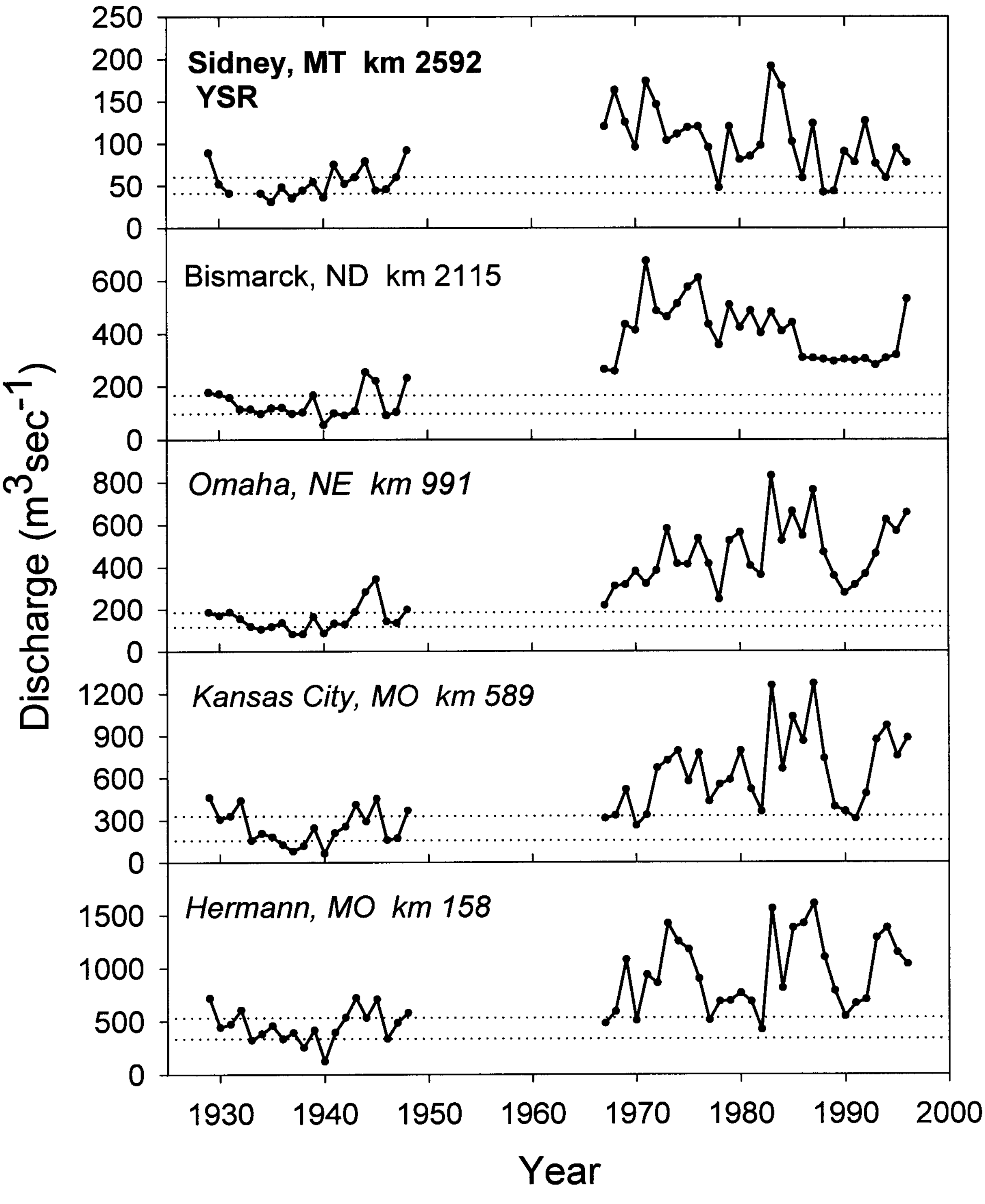

Fig. 6. Annual minimum 7-day median discharge at five stations along the Missouri and lower Yellowstone rivers (YSR) before (1929-1948) and after (1967-1996) flow regulation. The horizontal lines identify a target range of acceptable variability for the post-regulation period. Refer to Fig. 4 for further explanation.

channelized section, but then decreased again from *589KC* downriver. Hydrologic alteration in annual maximum flows at least–impacted stations ranged from 27% more years within the pre–regulation 25-75th%ile than expected to 20% less years than expected. Most regulated river stations exhibited a greater alteration in medians of annual maximum flows than least-impacted sites. Fewer years than expected were within the pre-regulation 25th–75th%ile range for 1- and 7-day averaging periods of median annual maxima for inter-reservoir stations and, at 2115BM to *991OM* between 60 and 100% of post-dam years were less than the 1- and 7-day 25th%ile (Fig. 5). The river from Kansas City (*589KC*) to the mouth showed a different trend with a higher number of post-regulation years falling within the target 25th-75th%iles of the 1- to 30-day averaging windows of maximum discharge than before flow regulation.

Post-regulation medians of annual minimum flows for 1-, 7- (Fig. 6), and 30-day averaging intervals at all study gages were higher than pre-dam medians, over 100% greater at many stations (Table 6). The locations with the smallest increases in annual minimum flows (although still ranging between 41 and 136% higher) were the two least-impacted sites and the lowermost stations *317BV* and *158HM*. Over 50% of post-dam years at all stations had fewer 1-, 7-, and 30-day annual minimum flows within the pre-dam 25-75th%iles than expected; all 30 post-dam years were above the target window for one or more of the annual minimum flow durations at six of the inter-reservoir and channelized river stations (Table 6, Fig. 6).

Timing of annual discharge extremes

Median date of the annual maximum daily discharge before flow regulation occurred within the same three weeks among all stations except 1297YT, ranging between Julian day 142 and 166

(21 May to 14 June). The median date of discharge maxima at 1297YT was 10 April. However, the timing of discharge maxima at 1297YT occurred in March during six years, in April for 5 years, and also in June for 6 years over the 20 years of pre-regulation data. Thus, the bimodal peaks of the flood pulse at 1297YT were historically more nearly equal than at stations up or downriver (Fig. 3). There were only minor differences in timing of the median Julian date of annual daily flow maxima following regulation at above-reservoir stations and also in the channelized river from *905NC* downriver (Table 6). However, variability in the date of annual maximum daily flow among years was generally higher in the channelized section following river impoundment (Table 6); fewer years than expected were within the pre-regulation 25th-75th percentiles (Fig. 7). Annual peak daily discharges occurred between 56 and 70 days earlier at inter-reservoir stations 2738WP and 2115BM, but 173 days later at station 1297YT below Gavins Point dam.

Prior to flow regulation, annual daily discharge minima occurred between mid December and early January (JD 345 to 4) at all stations except the uppermost Missouri River site (**3336FB**) where the median date of annual minimum daily discharge was 12 August. Median Julian date of annual flow minima occurred much earlier following dam operation at inter-reservoir stations 2738WP and 2115BM, and 80% more post-regulation years than expected were within the pre–regulation 25th-75th%iles for these two locations, even though variability in the timing of annual daily flow minima was much higher after regulation (Table 6). The gage below Gavins Point dam (1297YT) was again different from other below reservoir sites, as the timing of annual daily flow minima was delayed after flow regulation from Julian day 350 (15 December) to JD 71 (11 March), and 73% fewer years than expected fell within the pre-regulation 25-75th

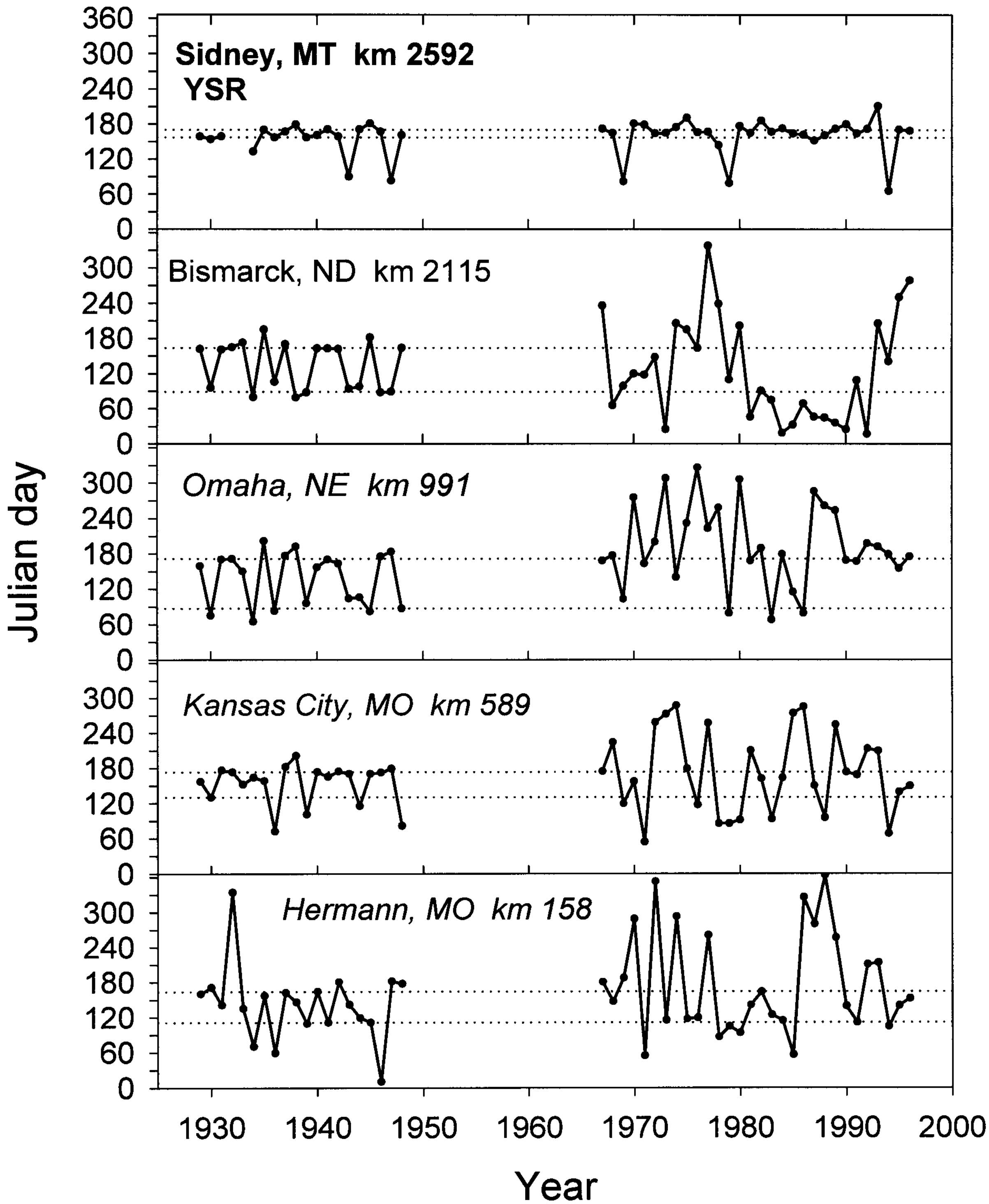

Fig. 7. Timing (Julian date) of each annual 1-day maximum discharge at five stations along the Missouri and lower Yellowstone rivers (YSR) before (1929-1948) and after (1967-1996) flow regulation. The horizontal lines identify a target range of acceptable variability for the post–regulation period. Refer to Fig. 4 for further explanation.

percentiles. Differences in the median Julian day of annual flow minima were <14% later in the year at all channelized river stations following flow regulation (Appendix A, Table A3). Variability in CD at channelized river sites ranged from +60 to -14%, except at *158HM* where it increased to 125%, and the percentage of post-regulation years within the 25th to 75th pre–regulation %iles was higher than expected at the three lowermost channelized stations (Table 6).

Median pre-dam date of lowest daily flow between May and October occurred from JD 223 to 283 (10 August-9 October) at all stations, was most common in September (7 of 11 stations), and generally occurred later in the season further downriver (October in the three lowermost stations). Timing of the 1967-1996 May-October daily flow minima was generally later than the 1929–1948 25-75th%iles for stations **3336FB** and 2738WP, was erratic at inter–reservoir station 2115BM, and occurred much earlier in the growing season at station 1297YT and all sites downriver (Fig. 8, Table 6). Specifically, Julian day of the growing season daily discharge minima following impoundment was earlier by 87 and 93 days at stations 1297YT and *991OM*, respectively, between 52 and 55 days earlier at stations *905NC*, *721SJ* and *589KC*, and 33 and 38 days earlier, respectively, at stations *317BV* and *158HM* (Appendix A, Table A3).

Frequency and duration of high- and low-flow pulses

Discharges selected as the minimum threshold to define the annual number and duration of high pulses occurred in June at all Missouri River stations. Least–impacted and inter-reservoir stations exhibited fewer (3-4 yr^{-1}) high-flow pulses before flow regulation than channelized river

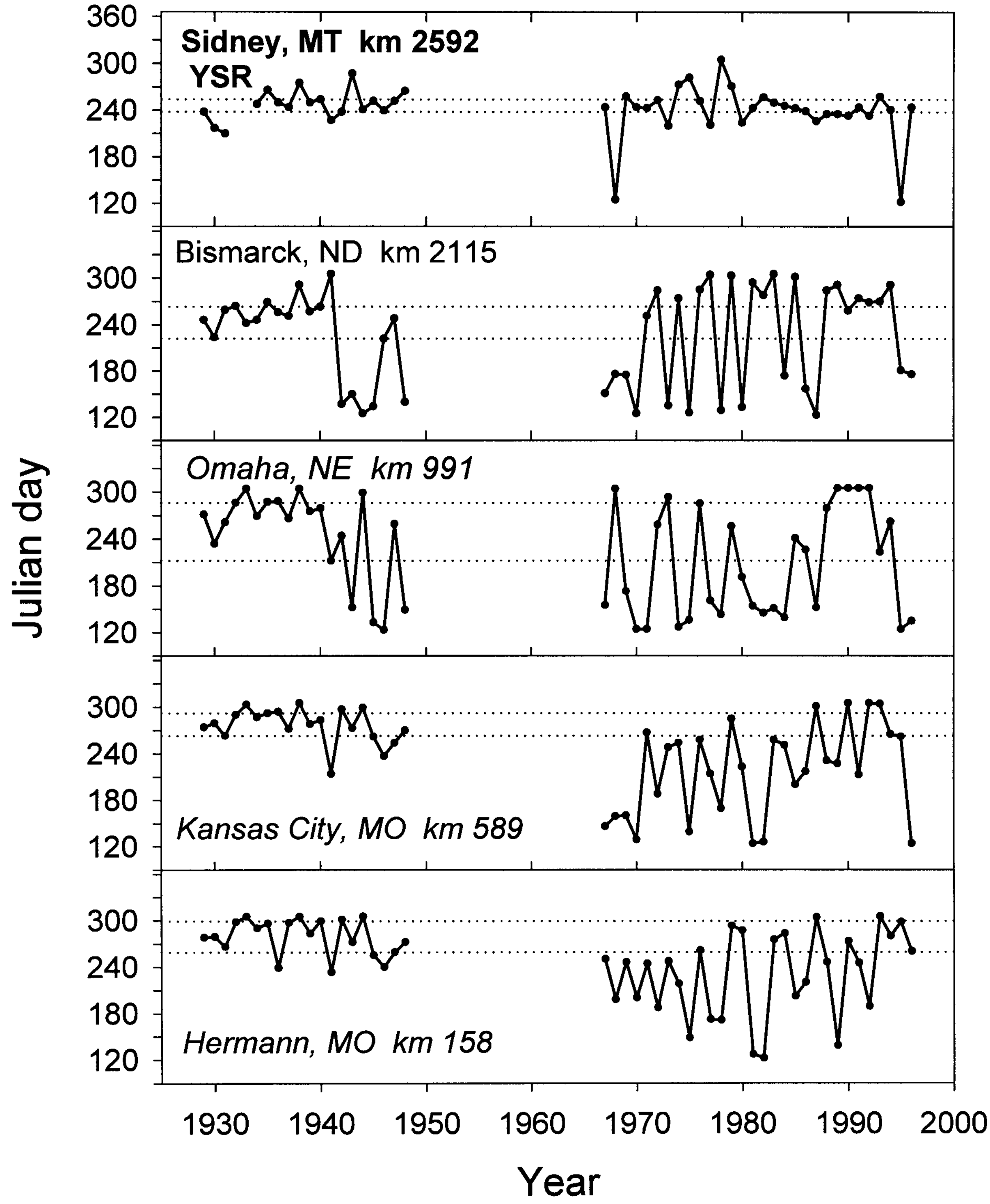

Fig. 8. Timing (Julian date) of each March-October (Julian day 122-305) 1-day minimum discharge at five stations along the Missouri and lower Yellowstone rivers (YSR) before (1929–1948) and after (1967-1996) flow regulation. The horizontal lines identify a target range of acceptable variability for the post-regulation period. Refer to Fig. 4 for further explanation.

stations (5-6 yr^{-1}). The median number of high-flow pulses per year doubled at the Missouri River least-impacted station **3336FB** (3 to 6 yr^{-1}) between the two time intervals, but remained constant at the Yellowstone River least-impacted station (**2592SN**). Frequency of high-flow pulses increased following flow regulation at inter-reservoir stations 2738WP and 2115BM, decreased at inter-reservoir and channelized stations 1297YT, *991OM* and *905NC*, and increased at three of the four lower-basin channelized stations (*721SJ, 317BV, 158HM*). Variability in the number of high-flow pulses per year increased by over 100% following flow regulation at inter–reservoir and channelized river stations 2115BM to *905NC,* compared to less than 35% at least-impacted upper basin sites (Fig. 9).

Median duration of high-flow pulses before impoundment ranged from 12 to 17 days yr^{-1} at stations **3336FB** to 1297YT and decreased downriver to 7-9 days yr^{-1} at stations *991OM–158HM* (Appendix A, Table A4). After impoundment, the median duration of high–flow pulses decreased (-3 to -48%) at 6 of the 7 stations between **3336FB** and *905NC*, except station **2592SN** on the Yellowstone River where the duration of high pulses increased by 24%. In contrast, the length of high-flow pulses increased from 5 to 20% at the four lowermost flow-regulated and channelized stations (*721SJ* to *158HM*) during 1967-1996. The number of days per year of high-flow pulses at the Yellowstone River site (**2592SN**) and the three lowermost channelized river stations *(589KC, 317BV* and *158HM),* were within the pre–regulation 25-75th%iles for over 60% of post–regulation years. In summary, the number of high-flow pulses per year generally increased between the two time periods, but their length was shorter at the two least-regulated stations and the two upper river, inter-reservoir sites. Both the number per year and duration of high-flow pulses were reduced below Gavins Point dam at

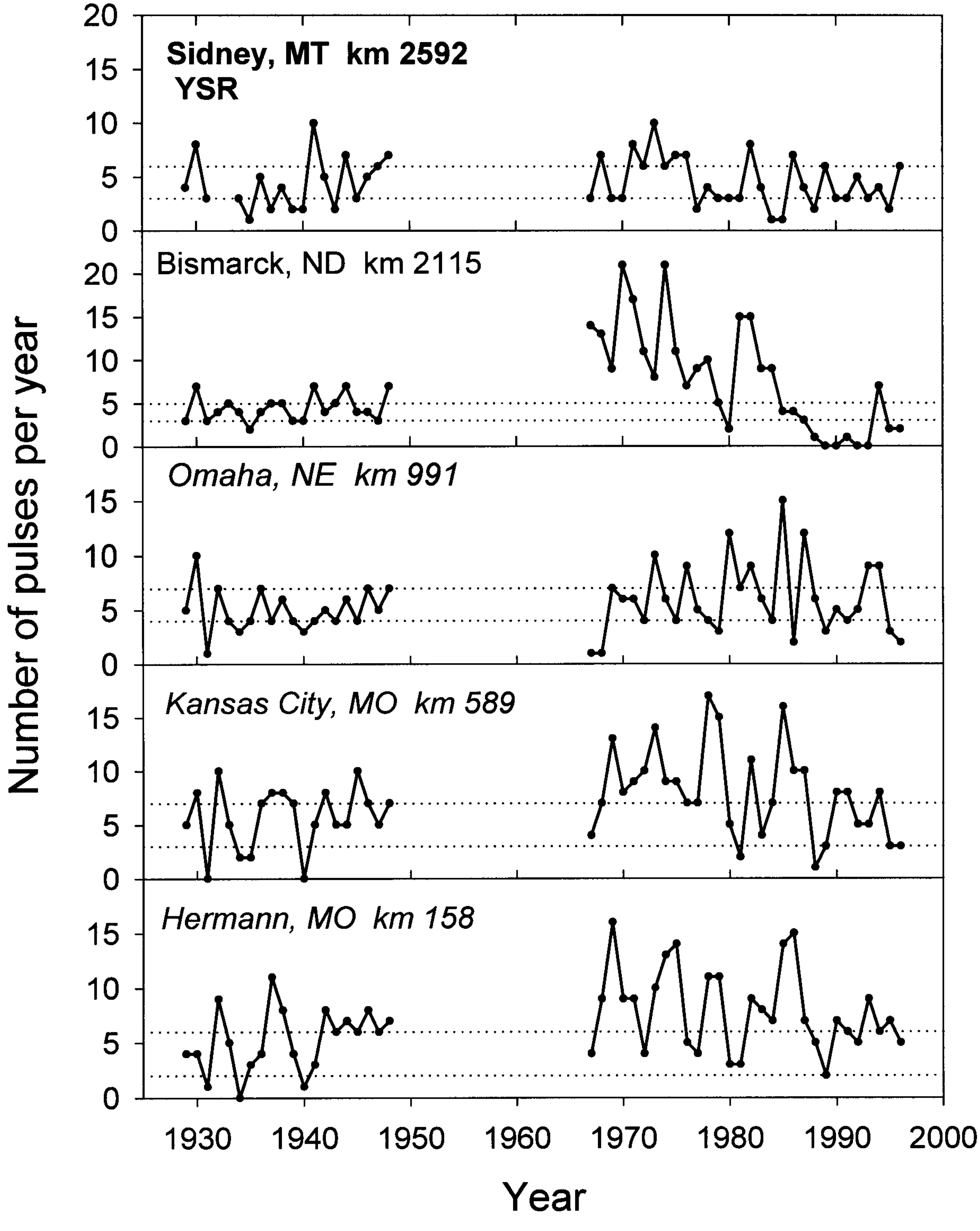

Fig. 9. Annual number of high-flow pulses at five stations along the Missouri and lower Yellowstone rivers (YSR) before (1929-1948) and after (1967-1996) flow regulation. The horizontal lines identify a target range of acceptable variability for the post-regulation period. Refer to Fig. 4 for further explanation.

station 1297YT, while the number per year and duration of high-flow pulses generally increased between 1929-1948 and 1967-1996 at the four furthest down-river gages (*721SJ-158HM*).

The number of low-flow pulses per year decreased following flow regulation at 10 of the 11 stations (Table 6). This reduction was smallest at the two above-reservoir stations, and the lowermost river gage (*158HM*). The post-dam decrease in number of low-flow pulses per year was highest (-40 to -78%) at inter-reservoir and channelized river stations, with the exception of 2115BM (Fig. 10). Variability in the number of low-flow pulses per year generally increased during the reservoir operation period, except at *158HM* were the CD decreased. Fewer post–regulation years than expected for most stations were within the 25-75th%ile target range for the number of low-flow pulses and the decrease in %HA was lowest at least-impacted site **2592SN**.

Changes in the duration of annual low-flow pulses were recorded between pre- and post–regulation intervals, but were variable along the river continuum (Table 6). Length of low–flow pulses following regulation was 45 to 77% shorter at the two above reservoir stations and the two upper most inter-reservoir gages. Below Gavins Point dam the pattern was reversed, the duration of low-flow pulses increasing by over 75% at stations 1297YT, *991OM*, and *905NC*. This increase in duration of low-flow pulses was dampened downriver until it again decreased at the two lower-most stations (*317BV*, *158HM*). So, while there was a general basin-wide reduction in the number of low-flow pulses between the pre- and post-dam intervals, their duration showed a complex longitudinal pattern: decreasing, increasing, and then decreasing again.

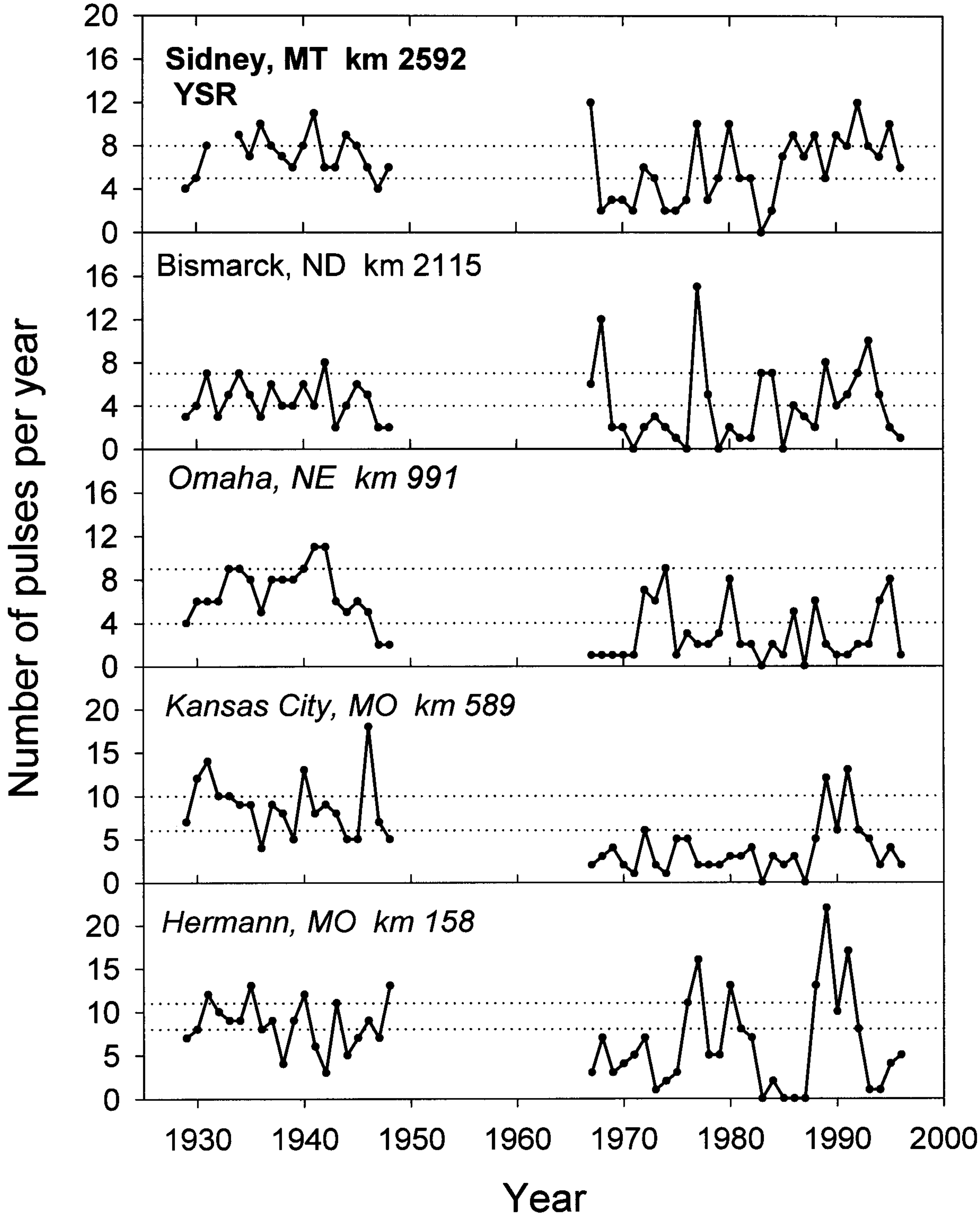

Fig. 10. Annual number of low-flow pulses at five stations along the Missouri and lower Yellowstone rivers (YSR) before (1929-1948) and after (1967-1996) flow regulation. The horizontal lines identify a target range of acceptable variability for the post-regulation period. Refer to Fig. 4 for further explanation.

Rate and frequency of change in discharge

Rates of change in river flow were the only hydrologic parameters analyzed using parametric statistics and the pattern of results were similar for both discharge rises and falls (Table 6). Mean rates of discharge rises and falls were between 15 and 34% lower and the mean number of flow reversals per year decreased slightly (4-6% less) during 1967-1996 at the two least-impacted upper–basin stations. There was a more pronounced post-regulation reduction in rise and fall rates at inter–reservoir and upper-channelized river sites than at least-impacted stations (Fig. 11) and between 50 and 100% fewer years were observed within the pre-regulation %HA target window at stations 2115BM to *905NC* (Table 6). The post-regulation reduction in mean rates of discharge change became progressively less proceeding downriver from 1297YT to 721SJ–589KC, while below 589KC (*317BV* and *158HM)* the mean rate of discharge change increased (Table 6). Additionally, more post-regulation years were within the pre-regulation target windows at the two lowermost sites, while fewer years than expected were within the window at regulated river stations upstream from *721SJ.*

More flow reversals per year were observed following regulation at stations downstream from dams, but this increase gradually diminished to only 14% more pulses per year after regulation at station *158HM* (Fig. 12). Similarly, alteration in number of flow reversals per year between the two time periods was highest at inter-reservoir stations and decreased in a linear fashion down river to *158HM.*

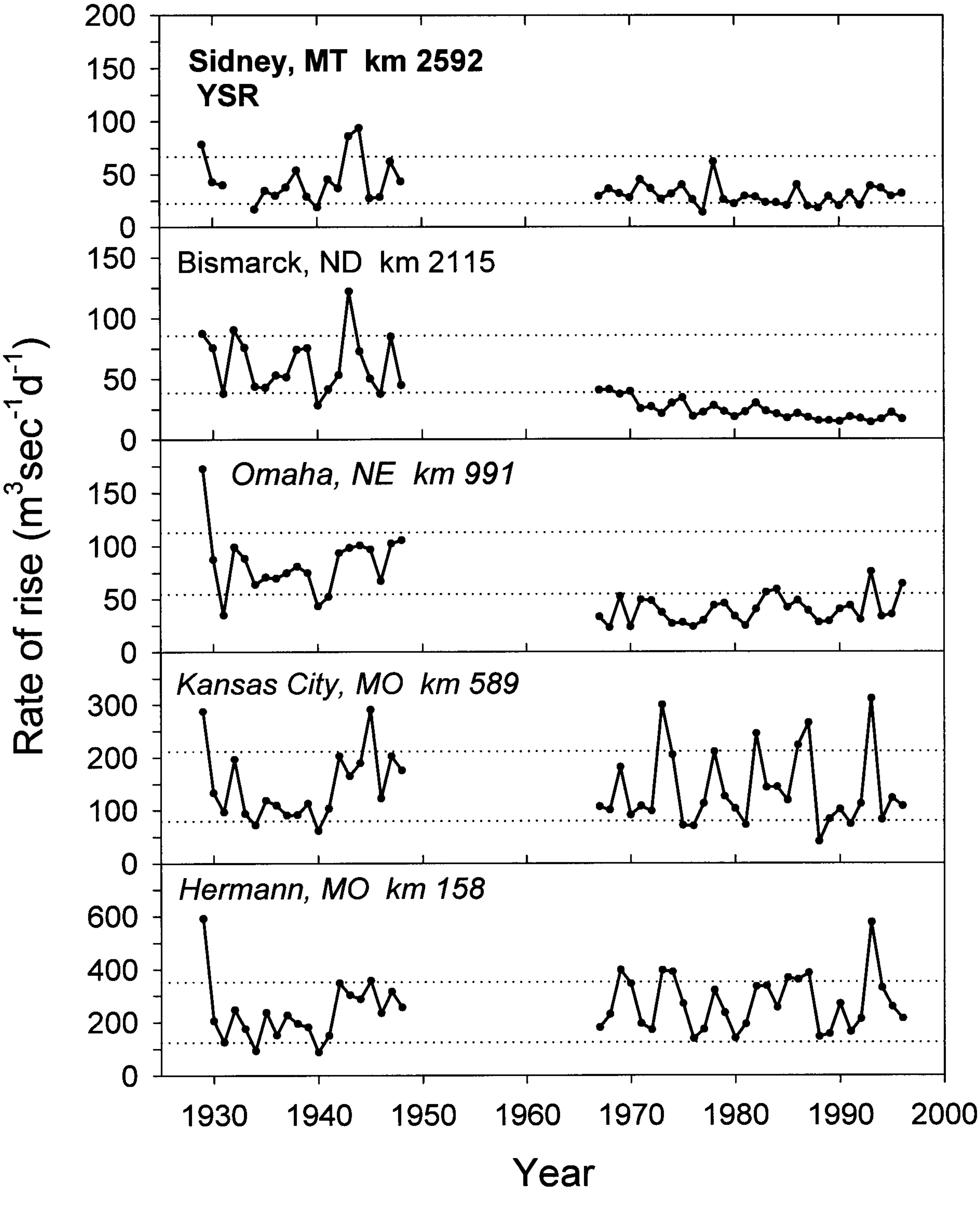

Fig. 11. Annual mean rate of discharge rise to five stations along the Missouri and lower Yellowstone rivers (YSR) before (1929-1948) and after (1967-1996) flow regulation. The horizontal lines identify a target range of acceptable variability for the post-regulation period. Refer to Fig. 4 for further explanation.

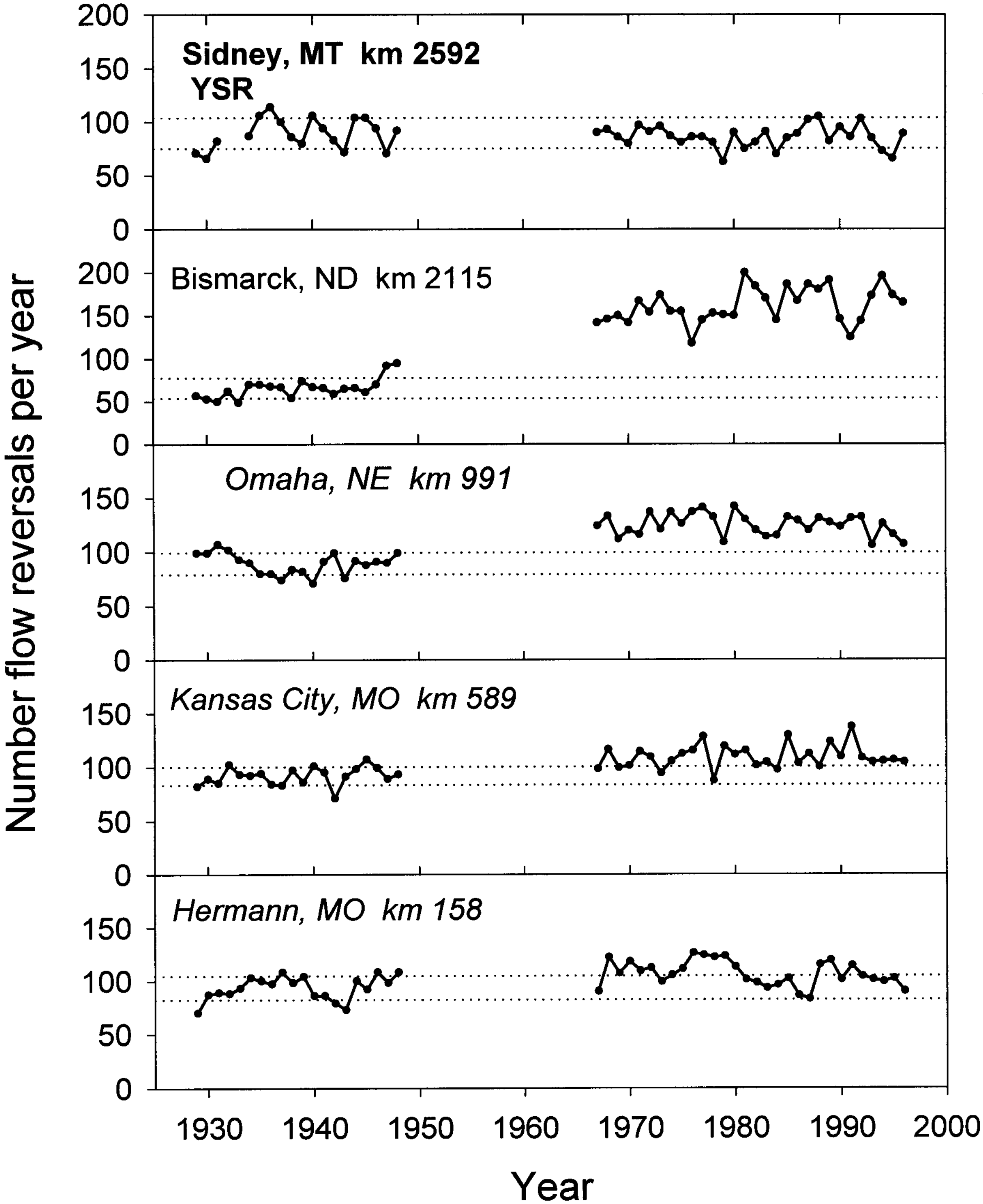

Fig. 12. Annual mean number of flow reversals at five stations along the Missouri and lower Yellowstone rivers (YSR) before (1929-1948) and after (1967-1996) flow regulation. The horizontal lines identify a target range of acceptable variability for the post-regulation period. Refer to Fig. 4 for further explanation.

Basin wide summary

Major differences in hydrologic indicators between pre- and post-regulation for the 11 stations are emphasized by reporting %HA for Groups 1-5 hydrologic indicators ranked high or extreme (Table 7). These include variables and stations where >50% more post-regulation years than expected (>22 of the 30 post-regulation years for Groups 1-4) were within or without the RVA target window (25th-75th%ile for Groups 1-4, $\pm$1 SD for Group 5). Additionally, for each of these cases we identified the direction of change (+ for positive, - for negative) for the post–regulation median or mean relative to pre-regulation conditions. A "o" indicates that the post-impoundment change in median or mean values was $\leq \pm$20% of the pre-impoundment measure. Hydrologic alteration between the two intervals in these cases was great, and post–regulation dispersion (CD or CV) was high, but there was little directional trend in the post–regulation median or mean.

Mean annual discharge for all stations along the Missouri River was higher from 1967 to 1996 than between 1929 and 1948, but noticeably less so at **2592SN**, the only station with no upriver impoundments. Flow regulation of the mainstem Missouri River was associated with significant alterations in many of the 32 hydrologic indicators (Table 7). Most notably, these were: (1) a reduction in the magnitude (i.e., lower high flows) and duration of the annual flood pulse; (2) an increase in the magnitude (i.e., higher low flows) and duration of annual discharge minima; (3) a reduction in the frequency of annual daily low-flow pulses and earlier timing of growing season daily low-flow pulses; and (4) a general increase in the frequency of discharge reversals per year coupled with a reduction in the rate of change in river flows. Collectively,

Table 7. Summary of flow alterations between pre- (Oct 1929-Sep 1948) and post- (Oct 1967-Sep 1996) regulation intervals for five groups of hydrologic variables at 11 stations along the Missouri and lower Yellowstone (**2592SN**) rivers. Hydrologic variables included are where >50% of post-regulation years than expected were within or without the RVA target window (25th-75th percentile for Groups 1-4, ± 1 SD for Group 5). The direction of change for the post-regulation median or mean relative to pre-regulation conditions is shown as + or -. A "o" indicates that the post-impoundment change was $\leq \pm 20\%$ of the pre-impoundment median or mean. JD = Julian date.

Station	Group 1 - Magnitude of monthly discharge extremes[1]		Group 2 - Magnitude & duration of annual discharge extremes		Group 3 - Timing of annual discharge extremes			Group 4 - Frequency & duration of high & low pulses				Group 5 - Rate & frequency of hydrograph changes		
			Max (d)[2]	Min (d)	JD annual Max	JD annual Min	JD Mar-Oct Min	High pulse Count	High pulse Dur.	Low pulse Count	Low pulse Dur.	Rise rate	Fall rate	No. flow reversals
Least-impacted														
3336FB	1,2,4,5,8,9,12	+		1,7,30 +	o		o	+						
2592SN	1,2,12	+		1,7,30 +										
Inter-reservoir														
2738WP	1,2,3,5,8,9,11, 12	+		1,7,30 +		-	+			-	-			+
	6	o												
2115BM	1,2,12	+	1,7 -	1,7,30 +		-	o	+			-	-	-	+
	6,7	-												
1297YT	1,2,4,8,9,10, 11,12	+	1,7 -	1,7,30 +	+	+	-		o	-	+	-	-	+
	3,7	o												
	6	-												
Below reservoir, channelized														
991OM	1,2,8,9,10,11,12	+	1,7 -	1,7,30 +		o	-		-	-	+	-	-	+
	3,4	o		.										
905NC	1,8,9,10,11,12	+		1,7,30 +		o	-	-	-	-	+		-	+
	7	o												
721SJ	1,8,9,10,11,12	+		1,7,30 +			-			-	+			+
	7	o												
589KC	1,8,9,10,11,12	+		1,7,30 +			-			-				+
	7	o												
317BV	1,2,8,9,10,11,12	+	1,7 +	1,7,30 +		o	o							
158HM	8,9,10,11,12	+	1,7 +	1,7,30 +		o			-	-				

[1]Numbers indicate months: 1=Jan, 2=Feb, etc.; [2]d=day (1-day, 7-day, or 30-day averaging interval).

hydrologic alterations were lowest at least-impacted station **2592SN**, most severe in the inter–reservoir and upper channelized river sections, and were dampened in the lowermost channelized river stations (Fig. 13). Least-impacted station **3336FB**, below Canyon Ferry Reservoir, showed a composite hydrologic alteration much higher than least-impacted site **2592SN** and similar to that of the four lowermost channelized river stations. Higher post-regulation discharge throughout most of the Missouri River catchment, but to a much lesser extent in the Yellowstone River basin, appeared to interact with reservoir operations to influence measures of hydrologic alteration between the two time intervals.

Discussion

Alterations in seasonal flow patterns and ecological effects

Our characterization of the historical Missouri River's flow regime between 1929 and 1948 shows the system to be more complex than previously reported (Hesse *et al.*, 1989; Schmulbach *et al.*, 1992; Hesse & Mestl, 1993; Galat *et al.*, 1996). The upper Missouri River annual flood pulse at Ft. Benton, MT (**3336FB**), was historically unimodal and remains so. Discharge began gradually to increase in March with ice break up (or "ice-out") and runoff from prairie snow melt, increased more abruptly in May, peaked in June due to Rocky Mountain snowmelt and declined in July. In contrast, the unregulated lower Yellowstone River (**2592SN**) showed a bimodal annual flood pulse with peaks in March and June. The importance of the Yellowstone River discharge to the Missouri River is demonstrated by the Missouri's annual flood pulse remaining distinctly bimodal in the middle- and most of the lower-river sections. However, our analysis showed that the initial flow peak frequently occurred in April, not March as others

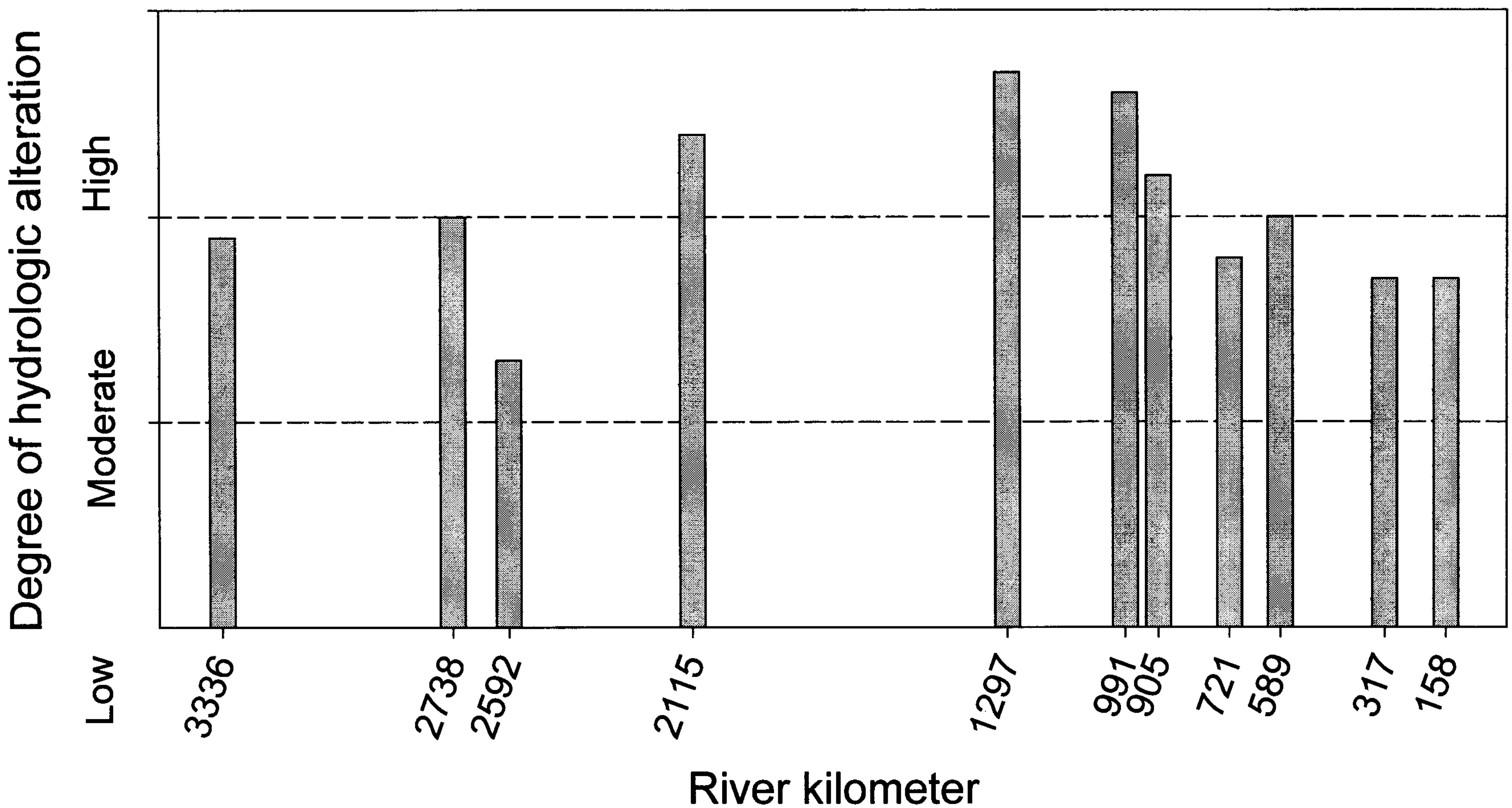

Fig. 13. Mean of ranked percentages of hydrologic alteration for the 1967-1996 post-regulation period across five groups of hydrologic indicators for 11 stations along the Missouri and lower Yellowstone rivers. Low alteration indicates that annual values for the average of all groups of post-regulation hydrologic indicators fell within the observed pre-regulation range of hydrologic alteration of 0-25% more of less often than expected, moderate: 26-50%, high: 51-75%, and extreme: 76-100%.

have reported. The bimodal pattern became less pronounced going downriver, so that near the Missouri River's confluence with the Mississippi River (*158HM*), the flood pulse was more unimodal with a plateau, rather than a dip, in May. The initial rise of the annual flood pulse in the lower basin was more abrupt in March than in the upper and middle basins, but like the upper and middle sections, it peaked in June and declined in July. The lower Missouri River within Kansas and Missouri seldom freezes over in winter and there is little winter snowpack, so there is no regional spring ice-out and snowmelt as in the middle and upper basins. The protracted annual flood pulse in the lower Missouri River is a temporally cumulative result of complex precipitation and climatic patterns throughout the catchment: spring ice-out in the upper and middle basins, spring snowmelt in the middle basin, runoff from spring rains in the lower basin, and runoff from June snowmelt in the upper basin. We expect the pre-regulation annual flow regime in the middle-river section was more bimodal than elsewhere because a spring rainy season is absent in the Great Plains Province.

The importance of a predictable annual flood pulse to reproduction of fishes in large floodplain rivers is well documented (Junk *et al.*, 1989; Ward, 1989; Welcomme *et al.*, 1989; Schlosser, 1991; Bayley & Li, 1992; Johnson *et al.*, 1995; Sparks, 1995; Lorenz *et al.*, 1997; Sparks *et al.*, 1998) and is the basis of the "flood-pulse advantage" observed in the high production of fishes in large river-floodplain systems (Bayley 1991). If the tenets of the flood–pulse concept are applicable to the Missouri River hydrosystem, we hypothesize that the depressed annual flood pulse has had the greatest negative impact on recruitment and production of native river-floodplain fishes in the middle Missouri River relative to the upper and lower sections. We are now testing this hypothesis by characterizing fish population dynamics along the entire Missouri River continuum using standardized collection and analysis techniques (Dieterman *et al.*, 1997).

The IHA analysis also showed there was historically a small fall increase in discharge along the lowermost Missouri River, similar to that reported by Sparks *et al.* (1990) and Sparks (1995) for the nearby upper Mississippi River. This small pulse is regional and due to the onset of autumn rains in the well-watered Central Lowlands and Interior Highlands physiographic provinces (Galat *et al.*, 1998). A fall flow pulse is important to provide fishes access to wintering habitats on the floodplain and in backwaters before cold water temperatures reduce their swimming ability (Bodensteiner & Lewis, 1992). Furthermore, it inundated annual moist–soil vegetation in floodplain wetlands, providing forage to fall migrating waterfowl. This historically small autumn flow pulse inundated floodplain wetlands to a shallower depth than the subsequent large June pulse with the result that forage remained available for waterfowl on their return migration the following spring (Sparks, 1992; Galat *et al.*, 1998). Flow releases for navigation and levees that disconnect the lower Missouri River from its floodplain wetlands have largely eliminated this fall river rise and the benefits to fish and wildlife it once provided.

Assessment of intra-annual flow patterns using the IHA method has also quantified alteration of several ecologically important summer low-flow variables and shown that changes are widespread over the regulated Missouri River. Sustained reservoir water releases during the naturally low-water season cause protracted flooding of about two–thirds of the Missouri River and may be as pervasive and damaging a disturbance as reduction of the annual June flood pulse.

Circumstantial evidence for this hypothesis comes from the native fish and bird community that reproduces in or along the Missouri and lower Yellowstone rivers (Table 8).

Table 8. Summary of fishes and birds that reproduce in or along the mainstem Missouri and lower Yellowstone rivers that were federally listed as candidate (C1, C2), threatened (T), or endangered (E) as of 1995. Fishes are placed into habitat use guilds of Bain (1992) as fluvial specialists (FS) or fluvial dependent (FD) based on macrohabitat use and reproductive requirements compiled from Pflieger (1971; 1997). Birds are identified as nesting on sand islands or bars (S) or elsewhere (E). Sources: Whitmore and Keenlyne (1990), U.S. Fish and Wildlife Service (1994; 1995).

Common name Guild	Scientific name	Status	
Fishes			
Lake sturgeon	*Acipenser fluvescens*	C2	FD
Pallid sturgeon	*Scaphirhynchus albus*	E	FS
Paddlefish	*Polyodon spathula*	C2	FD
Western silvery minnow	*Hybognathus argyritus*	C2	FS
Plains minnow	*Hybognathus placitus*	C2	FS
Sturgeon chub	*Macrhybopsis gleida*	C1	FS
Sicklefin chub	*Macrhybopsis meeki*	C1	FS
Flathead chub	*Platygobio gracilis*	C2	FS
Blue sucker	*Cycleptus elongatus*	C2	FS
Birds			
Interior least tern	*Sterna antillarum*	E	S
Piping plover	*Charadrius melodus*	T	S
Bald eagle	*Haliaeetus leucocephalus*	E	E
Peregrine falcon	*Falco peregrinus*	E	E

Based on adult habitat use and reproductive requirements described in Pflieger (1971, 1997), we identified as "fluvial specialists" (Table 8) seven of the nine fishes federally listed as candidate, threatened or endangered (U.S. Fish & Wildlife Service 1994; 1995). Fluvial specialists use flowing water habitats throughout life (Bain, 1992; Kingsolving & Bain, 1993). The remaining two species, lake sturgeon and paddlefish, are considered "fluvial dependent", requiring flowing-water at some point in their life cycle (Bain, 1992; Kingsolving & Bain, 1993). Both fishes reproduce in flowing waters and may migrate into tributary streams to spawn. All nine fishes are capable of completing their entire life-cycle within the channel complex and are included in Pflieger's (1971) "Big River Faunal Group." Loss of a river-floodplain connection due to reduction of the annual flood pulse should have less direct affect on their spawning success than on floodplain dependent species. However, the annual flood pulse remains an important cue to initiate spawning migrations for many fluvial specialist and fluvial dependent fishes (Welcomme 1985, Junk et al. 1989).

Loss of the braided channel geometry of the lower Missouri River through channelization has eliminated most sand island and shallow in-channel habitats used by riverine fishes for spawning and nursery. What few low-elevation sand islands and associated shoals that remain are now flooded or their surface area reduced during part (July-September) of the reproductive season for many riverine fishes, as well as for birds (Table 8) and turtles (Galat *et al.*, 1998) that make similar use of these critical habitats. Additionally, protracted summer-fall high flows prevent germination of early-successional tree species (Johnson, 1992) and moist-soil annual vegetation in habitats that remain along the narrow, steep-sloped channel of the lower Missouri River.

Natural factors contribute to spatio-temporal variability in river flows

Station **2592SN** on the Yellowstone River was the only site we evaluated where no upstream mainstem impoundments were present and it showed the lowest degree of hydrologic alteration between the two time intervals (Fig. 13). Other locations with the lowest overall flow change were least-impacted site **3336FB**, and channelized river station *158HM*, the site farthest downriver from mainstem reservoirs. Impoundment of the upper Missouri River by Canyon Ferry and other smaller reservoirs appeared to influence hydrology at **3336FB** during the 1967-1996 interval as the post-regulation summer median flows were higher than before regulation at **3336FB,** but not at **2592SN**. The uppermost Missouri River reservoirs operate primarily for irrigation, storing snowmelt for release to downstream users during the May–October growing season.

Proceeding downriver from the last mainstem dam, Gavins Point (km 1305), overall flow alteration between 1967 and 1996 declined from that observed at inter-reservoir sites. Hydrologic variability was less from *721SJ* to the mouth than between the large mainstem reservoirs and was similar to, or lower than, the upstream least-impacted Missouri River site at **3336FB**. However, sources of hydrologic alteration differed somewhat among the channelized river stations and between them and **3336FB** (Table 7). Notably, post-regulation magnitude and duration of annual maximum flows were higher at *317BV* and *158HM* than at other channelized sites because these locations were more affected by climatically driven flooding in 1993, 1995 and 1996 (Parrett *et al.*, 1993; Galat *et al.*, 1998).

Flow differences were moderate to extreme comparing the 1929-1948 interval to 1967–1996 at all sites examined, including least-impacted site **2592SN**. Consequently, caution must be used in attributing hydrologic alteration observed among sites and between the two time intervals solely to flow regulation. While mainstem impoundment, flow regulation, and changes in land use greatly influenced hydrologic variability of the Missouri River, at least two natural factors also contributed to the spatio-temporal differences observed in hydrologic indicators. Basin-wide precipitation and runoff differed between the two time intervals and hydrology is inherently variable along the Missouri River continuum.

The "dust bowl" droughts of the 1930s occurred during the pre-regulation period and recurrent flooding in the 1990s was prevalent during the post-regulation interval. Qi Hu *et al.* (1998) analyzed interdecadal variations in precipitation over the last century in the central U.S., including the lower Missouri River basin states of Kansas, Nebraska, Iowa, and Missouri. They concluded that there has been a trend in the region's annual mean precipitation and that it has changed from a decrease before the mid-1960s to an increase thereafter. Thus, the increase in low-flow discharge observed between 1967 and 1996, and most pronounced at inter-reservoir and channelized sites, appears to be a cumulative effect of mainstem flow regulation operating within the context of a catchment wide increase in precipitation. This conclusion illustrates the importance of including least-impacted sites in analyses of historical flow variability to normalize or filter out temporal climatic variation.

A paradigm of the flood-pulse concept is that hydrological buffering of a large catchment area results in smooth and predictable flooding and that effects of seasonal climatic changes are observed downstream only after several weeks or months in unaltered large–floodplain rivers in temperate and tropical regions (Junk *et al.*, 1989). This has been shown graphically for the pre–regulation upper Mississippi (Sparks, 1992; Sparks *et al.*, 1998) and Illinois Rivers (Sparks, 1995). In contrast, timing of the pre-regulation median annual discharge maxima at 10 of 11 locations over 3178 kilometers of the Missouri and lower Yellowstone rivers all occurred within

24 days and there was no longitudinal time lag. Additionally, IHA variables along the Missouri River continuum did not show a longitudinal increase in predictability before flow regulation. Indices of dispersion (CD and CV, Tables 5 and 6 and Appendices) and the relative ranges of the pre-regulation 25-75th%iles among stations (Figs. 4-12) either showed no longitudinal pattern or upper- and lower-most stations exhibited the greatest flow variability for most hydrologic indicators.

The Missouri River does not fit neatly into the flood-pulse paradigm because it arises in the well–watered Rocky Mountains and then flows over 1000 km through the semi-arid Great Plains. Consequently, its middle section is largely allogenic (flow arises from outside the section), analogous to a dryland river as described by Walker *et al.* (1995). However, tributary influx to the Missouri River is highest in the lowermost section (Fig. 3), so that variability in the frequency and duration of high-flow pulses and discharge is also high (Table 4). Our assessment of 50 years of Missouri River hydrology illustrates that the influence of reservoir operations on the annual flood pulse was partially offset by tributary influx downriver from Kansas City (*589KC*) during the wet period of 1967-1996.

Hughes *et al.* (1986; 1990) and Hughes (1995) recommended that only regional or ecoregional references be used to develop biological criteria for lakes and rivers. Our empirical results are in concurrence and indicate that distant locations are inappropriate spatial references for large rivers where natural longitudinal and geographic variability are great. The mainstem Missouri River occupies nine of Omernik's (1987) 76 ecoregions within the conterminous United States. Additionally, spatio-temporal differences in precipitation can confound applicability of historical data to establishing reference conditions. Prescribing initial flow targets from least–impacted locations and historical data at the landscape scale for large rivers maximizes use of available information. However, these sources are not without their shortcomings and, therefore, should not be the sole criteria for designing flow guidelines.

Preliminary flow recommendations within an adaptive management framework

The IHA and RVA methods are comprehensive, easy to apply techniques to assess the hydrological and, by inference, the ecological integrity of running waters. The suite of hydrologic indicators calculated enabled us to identify both spatial and temporal differences in discharge patterns along the entire Missouri River. A particular value of these methods is that they identify both increases and decreases in hydrologic variability and give high- and low-flow alterations equal weight. The idea of a human-induced disturbance as an alteration from the natural range of flow variation is bi-directional. High flows during the historical low-flow season can have ecological consequences as harmful as a reduction in the annual flood pulse. This was the pattern most prevalent along the regulated Missouri River, although longitudinal differences were apparent. Additionally, factors like channelization, bank stabilization, levee construction, and changes in land use and land cover greatly influence the discharge-stage relationship, river-floodplain hydrology, and habitat availability and also need to be considered when designing, implementing, and refining flow-management guidelines.

Our assessment of hydrologic alteration along the Missouri River indicates that reservoir operations could be modified to more closely approximate the 1929-1948 flow regime of the Missouri River. If a management goal for the Missouri River is to establish a simulated natural riverine ecosystem (*sensu* Schmidt *et al.*, 1998), whereby operational flexibility within the existing reservoir complex is used to enhance river-floodplain natural resources, then the RVA targets reported as m^3 sec^{-1} (CMS) in Appendix A, Tables A1-A5 can be used as initial design guidelines. For example, target guidelines for Group 1-4 variables are that 50% of the years should fall between the Pre 25th%ile and Pre 75th%ile values, and for Group 5 variables, 67% of the years should fall between the Pre -1SD and Pre +1SD values. Identical guidelines, but in ft^3 sec^{-1} (CFS) can also be found in Appendix B for each station in the "RVA Targets" columns of either the "IHA Parametric RVA Scorecard" or "IHA Non-Parametric RVA Scorecard" Tables.

Overall ecological structure and function of the inter-reservoir and upper channelized river sections would benefit by controlled flooding through managed reservoir releases during June and July of some years, as well as by increasing the frequency and duration of annual high-flow pulses, and the annual rate of hydrograph rises and falls. All of the regulated Missouri River would benefit from reducing reservoir discharges in most, if not all, years from August through February, modifying the timing of releases and reducing the annual number of hydrograph reversals. These actions would increase frequency and reduce discharge of monthly and annual low flows, delay the timing of the growing season daily discharge minima, and reduce the frequency of flow reversals per year. Assessment of ecological responses to a reregulation of river flows that more closely approximates the natural flow regime should then be used in an adaptive fashion to further adjust reservoir operations.

The RVA results presented here provide a first approximation of flow recommendations that approach the 1929 to 1948 range of variability in magnitude, duration, timing, frequency and rate of change of river flows throughout the Missouri River catchment. Whether this period is an accurate representation of "natural" flows and therefore a suitable reference to design target flows must be decided by a management team.

Aspects of these ecologically based flow-management guidelines conflict with contemporary Missouri River reservoir management objectives of maximizing mid-summer power production in the middle river and providing summer-autumn flow releases for navigation in the lower river. We hope that consideration of the range of flow variability approach presented here and elsewhere (Richter *et al.*, 1998) will stimulate discussion among the various beneficiaries within and outside the Missouri River basin to reconcile these differences. Also, similar analyses of hydrologic variability are needed on other river systems to better define the geographic diversity of natural and altered flow regimes. Such assessments will assist development of integrated and adaptive hydro-ecological models to predict a range of structural and functional responses of river–floodplain biota to various flow management scenarios within a framework of broader policy issues and societal values.

Acknowledgments

We thank Tom Parks and Robert White for information on sources of flow alteration to the upper Missouri and lower Yellowstone rivers. Chuck Smythe and Brian Richter assisted in application of the IHA and RVA methods. Thai Ngu contributed to preparation of Figures, Pam Haverland assisted with data preparation, and Sandy Clark edited the manuscript. Lee Bergsted, Doug Dieterman, Robb Jacobson, Mark Pegg, Brian Richter, and Mike Ruggles reviewed the manuscript. Funding for this research was provided by the Missouri Department of Conservation to the University of Missouri. This article is a contribution from the Missouri Cooperative Fish and Wildlife Research Unit (U.S. Geological Survey-Biological Resources Division, Missouri Department of Conservation, University of Missouri, and Wildlife Management Institute cooperating).