Aquat. Sci. 65 (2003) 63–72
1015-1621/03/010063-10

Aquatic Sciences

Research Article

Hydrological alteration along the Missouri River Basin: A time series approach

Mark A. Pegg [1,*], Clay L. Pierce [1] and Anindya Roy [2]

[1] U.S. Geological Survey, Biological Resources Division, Iowa Cooperative Fish and Wildlife Research Unit, Department of Animal Ecology, Iowa State University, Ames, IA 50011, USA
[2] Department of Mathematics and Statistics, University of Maryland, Baltimore, MD 21250, USA

Received: 4 February 2002; revised manuscript accepted: 21 October 2002

Abstract. Human alteration of large rivers is commonplace, often resulting in significant changes in flow characteristics. We used a time series approach to examine daily mean flow data from locations throughout the mainstem Missouri River. Data from a pre-alteration period (1925–1948) were compared with a post-alteration period (1967–1996), with separate analyses conducted using either data from the entire year or restricted to the spring fish spawning period (1 April–30 June). Daily mean flows were significantly higher during the post-alteration period at all locations. Flow variability was markedly reduced during the post-alteration period as a probable result of flow regulation and climatological shifts. Daily mean flow during the spring fish spawning period was significantly lower during the post-alteration period at the most highly altered locations in the middle portion of the river, but unchanged at the least altered locations in the upper and lower portions of the river. Our data also corroborate other analyses, using alternate statistical approaches, that suggest similar changes to the Missouri River system. Our results suggest human alterations on the Missouri River, particularly in the middle portion most strongly affected by impoundments and channelization, have resulted in changes to the natural flow regime.

Key words. Hydrology; time series; human alteration.

Introduction

Human activities have directly altered the flow of large rivers for thousands of years (Petts et al., 1989). Lotic systems have been modified worldwide to meet flood control, navigation, water supply, power generation, and recreation demands. While there have been benefits to these management practices, there have also been costs. Modification to both river and riparian habitats can range from the relatively localized effects of small-scale grazing to the much broader effects of channelization and impoundment. As a result, many of the original defining physical and ecological characteristics of these managed systems have been profoundly altered (Poff et al., 1997).

Altered flow has been one of the primary consequences of impoundment and channelization. Impoundments designed primarily for flood control, navigation, and water supply tend to dampen natural flow variation by storing large amounts of water for later, controlled release (Bravard and Petts, 1996). Conversely, dams built for power generation tend to accentuate natural variability by creating daily high and low flow periods to meet electrical demands (Bravard and Petts, 1996). Channelization, accomplished by armoring the shorelines, diverting water out of side channels, and straightening the channel, also influences flow by facilitating rapid transport of water downstream. Other direct consequences of

* Corresponding author current address: Illinois Natural History Survey, Illinois River Biological Station, Havana, IL 62644, USA; e-mail: markpegg@staff.uiuc.edu.
Published on Web: March 19, 2003

channelization include loss of river connectivity to the floodplain (Ward and Stanford, 1995), changes in water quality (Whitley and Campbell, 1974), and loss of aquatic habitat (Mosley, 1983).

Flow in many large river systems is affected by a combination of alterations, including impoundments, channelized reaches, water diversions, and numerous landscape changes in the catchment. These alterations are likely to result in complex changes to the flow regime, and the precise nature of these changes may be difficult to predict. Many factors including flow reduction in impounded reaches, increased velocities in channelized reaches, loss of diverse habitat complexes, changes in runoff and sedimentation loading rates, and altered nutrient cycles, all a result of human alteration, create an environment seldom if ever historically experienced by the native fauna in these lotic systems (Ligon et al., 1995; Ibanez et al., 1996).

Poff et al. (1997) identified magnitude of discharge, frequency of flow extremes, duration of a given flow condition, timing of extremes, and the rate of change from one flow to another as major components of flow that regulate ecological processes. All or part of these five components have been used to evaluate various aspects of how flow has changed before and after large-scale management in lotic systems (Richter et al., 1996; Richter et al., 1997; Galat and Lipkin, 2000). Most of these studies used summary statistics and indices that define general hydrological conditions from daily flows to characterize the degree of hydrological alteration at several gauges within a system. For example, using the Index of Hydrological Alteration (IHA), Galat and Lipkin (2000) reported that Missouri River flows were most affected in reaches that were heavily influenced by reservoirs.

The literature is filled with commentary on the need to validate or at the least evaluate previous findings and techniques (e. g., Oreskes et. al., 1994; Stanley, 1995) yet published accounts are largely lacking in many disciplines. In this regard, we present an alternative method in an attempt to validate previous work assessing hydrological alteration along the Missouri River. Hydrological alterations made on the Missouri River have been qualitatively and/or regionally evaluated in several studies (Slizeski et al., 1982; Hesse and Mestl, 1993), but few published studies have attempted a more quantitative approach to assessing the extent of these alterations (e.g., Galat and Lipkin, 2000). Here, we present a different approach (time series modeling) than that of Galat and Lipkin (2000) to quantitatively test for differences in flow patterns associated with large-scale structural changes throughout the mainstem Missouri River. Our specific objectives were to (1) develop time series models of daily mean flow for 10 Missouri River locations with data series encompassing pre- and post-alteration periods, (2) test for significant differences in daily mean flow between pre- and post-alteration periods using data from the entire year, and (3) test for differences in daily mean flow between pre- and post-alteration periods using data restricted to the spring fish spawning season (1 April – 30 June). In accomplishing our objectives, we were able to look in detail at the dynamics of the daily flows and also able to compare the findings from the IHA approach to our time series approach.

Study area

The Missouri River is one of the largest rivers in North America, stretching over 3,768 km and draining about one sixth of the continental United States (Fig. 1). Historically, the Missouri River was characterized as a very turbid, meandering river as it flowed through the Great Plains of North America (Berner, 1951; Funk and Robinson, 1974). The onset of large-scale structural alteration in the early to mid 1900s on the Missouri River dramatically altered the pre-European settlement condition of this large floodplain river (Hesse, 1987). For example, channelization from the river's confluence with the Mississippi River to Sioux City, Iowa was conducted between 1927 and 1969 to allow deep-draft barge traffic (Schneiders, 1996). Six mainstem dams were also constructed between 1937 and 1963, primarily to control flooding and to provide adequate depth for navigation on the lower river (Galat et al., 1996). The associated reservoirs cover nearly half of the upper 2,500 km of the Missouri River (Morris et al., 1968). The result of these alterations has been a metamorphosis from a once natural, complex floodplain river to a relatively artificial, simple system (Whitley and Campbell, 1974), with division of the river into three management zones: an upper, relatively unaltered (or least altered) zone upstream from the reservoirs, a zone between the reservoirs where short stretches of unchannelized river remain, and a lower channelized zone (Fig. 1).

Methods

Flow data

Testing for differences in flow patterns resulting from human alterations requires pre- and post-alteration data. We obtained daily mean flow data for 10 Missouri River gauges (Fig. 1) from the U.S. Geological Survey (USGS) on-line database, and divided the data set into pre-alteration and post-alteration periods for further analysis. Construction of the impoundments and channelization primarily occurred in water year (October – September) 1948 through water year 1966 as the five lower reservoirs were being constructed and filled (Galat et al., 1996). We did not include these years in our analysis due to the po-

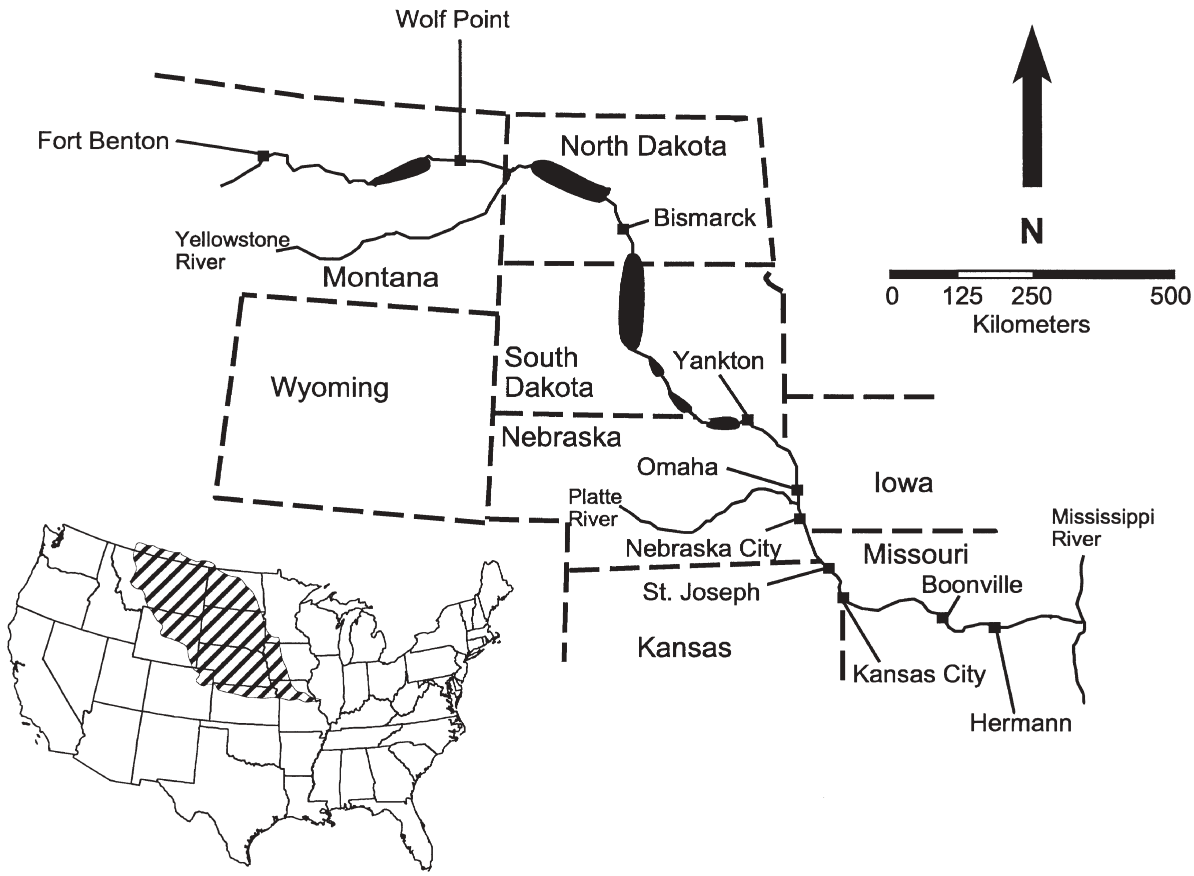

Figure 1. Location of gauges (■) on the Missouri river used to analyze the effects of human alteration on daily mean flow. Mainstem reservoirs are indicated by dark ovals. Inset shows location of the Missouri River basin within the United States.

tential influence of this 'filling effect' on daily flows. Thus, we considered data from before 1948 as pre-alteration and that after 1966 as post-alteration data.

The daily mean flow data record available during the pre-alteration period varied among gauges, with some gauges having only a few years (10–15), whereas one gauge had nearly 60 years of record. Comparing time series data of different lengths is possible, but simultaneous evaluation of several gauges along the length of the river was facilitated by making all data series similar lengths. The outcome was a slight loss of information, but the advantage is that the resulting series generally reflected the same chronological sequence of large-scale natural phenomena (e.g., low flows, floods). Therefore, we only used gauges that provided information for at least 18 of the 23 years immediately prior to 1948. These procedures yielded data sets from 10 gauges distributed throughout the mainstem Missouri River representing the three management zones (Fig. 1).

Statistical analyses

Our intent is to provide only a brief summary of our time series methods rather than a comprehensive overview. For further details, see Yevjevich (1984), Wei (1990), or SAS (1991). We followed the Box-Jenkins (Box and Jenkins, 1970) approach to identify the best time-series model. This procedure entailed identification of the underlying processes, estimation of model parameters, and diagnostic checks for goodness of fit. The identification procedure attempted to identify the process by which the series was driven. We then estimated model parameters after the underlying process was identified. Diagnostic checks in the form of autocorrelation plots, residual plots, and evaluation of summary statistics (e.g., Akaike's Information Criterion, Durbin-Watson statistic) were used to assess the model parameters. This process was repeated until the best fitting model was identified.

We first fit individual time series models to each alteration period for every gauge. Daily mean flows tend to be dependent upon prior daily flows making autoregressive (AR) models appropriate (Yevjevich, 1984). This class of model uses prior observations to estimate its current value in the prediction process (Wei, 1990). The general structure of an AR model is:

$$y_t = \theta_0 + \phi_1 y_{t-1} + \ldots + \phi_p y_{t-p} + a_t, \quad (1)$$

where y_t is the observed value at time t; θ_0 is a constant; values of ϕ are the model coefficients that relate the proportional effect each previous (lagged) observation has on y_t; p is the total number of lags; and a_t is a random error term.

Multiple-year hydrological data tend to have non-constant variance (termed "nonstationary") due to periodicities corresponding to seasonal climate fluctuations. We accounted for nonstationarity by using several sine/cosine transformations of the time variable to describe the flow characteristics at each gauge. Each data point had a series of paired transformations calculated as:

$$\sin(x) = \sin\left(x \cdot 2\pi \cdot \frac{t}{d}\right) \text{ and } \cos(x) = \left(x \cdot 2\pi \cdot \frac{t}{d}\right) \quad (2)$$

where x is the sequence number of the transformation (i.e., 1 for the first sin/cos transformation, 2 for the second, etc.), t is the time variable, and d is the number of days in one full period of record (here d = 365). We also used a variable time coefficient to account for any remaining unequal variances that remained after transformation.

We used the AUTOREG (SAS 1991) procedure to fit an initial AR model for each period and gauge and then graphically assessed the autocorrelation function (acf) to identify the number of parameters needed in each model. After model identification, we examined the model residuals to verify that there was no remaining correlation. Once the time series models and their parameters were identified, we individually tested each gauge against the hypothesis that daily mean flows were different between the two periods. We created an individual matrix for each flow period from the resulting time series models that included the time series model parameters, sine/cosine transformed data, and appropriate number of lagged flow values from the model. We then multiplied the pre- and post-alteration matrices using weighted least-squares regression, with the reciprocal of the variance (SAS 1990) from the original time series model as our weighting factor. This regression allowed us to make paired comparisons between the pre- and post-alteration period at each gauge because we could estimate the mean and standard deviation through the matrix multiplication process. We then used the resulting comparisons from these 10 gauges to evaluate trends in flow throughout the river. Significant differences were declared at $P \leq 0.10$.

We also tested for differences among flows between the pre- and post-alteration periods for the spring fish spawning season between 1 April and 30 June. This time frame was selected for two reasons. First, while not wholly encompassing all spawning activity, this period does cover a significant portion of the suitable and preferred temperatures when spawning is at least initiated for most species found in the Missouri River (e.g., data from Braaten, 2000). Second, this period hydrologically covers the spring flooding episodes believed to be important for spawning and rearing fish in large, floodplain rivers (Junk et al., 1989) and is also likely to be most affected by present management strategies. Our analyses were similar to Eqs. (1)–(2), with the exception that the variable 'd' used in the sine/cosine transformations was changed to reflect the number of days in the spring flow period (d = 91).

Results

Daily flows over the entire year

Figure 2 illustrates the daily mean flows for the pre- and post-alteration periods at four gauges representative of the major Missouri River flow patterns observed in our analyses. Visual inspection of Figure 2 indicates that flows in the middle reaches of the river (i.e., the inter-reservoir zone and the upper portions of the channelized zone) have changed dramatically between the pre- and post-alteration periods as evidenced by a decrease in flow variability during the post-alteration period. In contrast, flow variability has maintained some integrity between the two periods at Fort Benton (i.e., unaltered zone), the upper most gauge, and Hermann (i.e., channelized zone), the lower most gauge on the Missouri River (Figs. 1 and 2).

An autoregressive model with two lagged coefficients (AR(2) model) fit to the transformed data adequately defined the flow patterns for all gauges for both time periods. Autocorrelation and periodicity were generally removed by the transformation as indicated by the residual plots in our models (Fig. 3). As with mean flows (Fig. 2), the amount of variability in the residual plots is lower after alteration in the inter-reservoir and upper channelized zones of the river as represented by Bismarck, ND, and Omaha, NE (Fig. 3). Conversely, in the extreme upper and lower gauges on the river, residual variability is similar in pre- and post-alteration periods.

Daily mean flows were significantly higher during the post-alteration period at all gauges ($P < 0.10$; Table 1). Post-alteration daily flows averaged 16% higher than the pre-alteration flows at Bismarck, ND, and 10% higher at Yankton, SD (Table 1). The remaining gauges had daily mean flows during the post-alteration period that averaged from 30 to 45% higher than pre-alteration flows.

Daily flows during the spring fish spawning period

Graphical comparisons of pre- and post-alteration daily mean flows during the spring fish spawning season were qualitatively similar to those made over the entire year, with the most obvious changes appearing in the middle sections of the river. Autoregressive, AR(2), models pro-

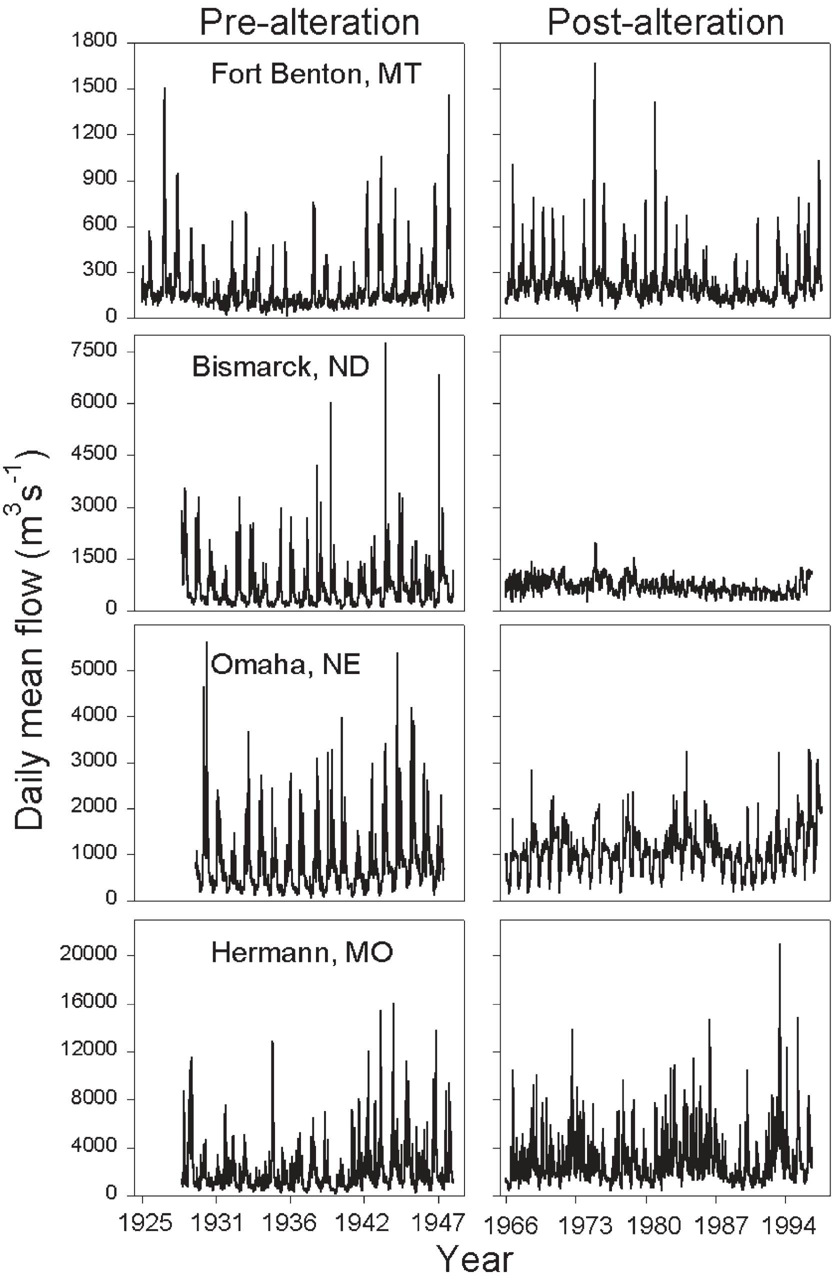

Figure 2. Daily mean flows during the pre-alteration (1925–1948) and post-alteration (1967–1996) periods at four representative gauges along the Missouri River.

vided adequate fits, and residual plots were similar to those in Figure 3. Average absolute percent differences between the two periods ranged from 2 to 32% which were generally less extreme than the average differences over the entire year (Table 2). However, tests for differences between pre- and post-alteration yielded quite different results compared to the annual scale (Table 2). Post-alteration, spring daily mean flows at the two uppermost gauges (Fort Benton, MT, and Wolf Point, MT) and the two lower most gauges (Boonville, MO, and Herman, MO) were not significantly different between the two time periods (Table 2). In contrast, gauges located in the middle portion of the river (Bismarck, ND, to Kansas City, MO) did significantly differ ($P < 0.10$) among flow periods, and percent change appeared to follow a longitudinal gradient from a high-negative to a low-positive. Spring spawning daily flows at Bismarck, ND, averaged 32% lower, Yankton, SD, averaged 28% lower, and Omaha, NE, averaged 5% lower during the post-alteration period; whereas, flows from Nebraska City, NE, to Kansas City, MO, averaged 5 to 7% higher during the post-alteration period. These differences are clearly de-

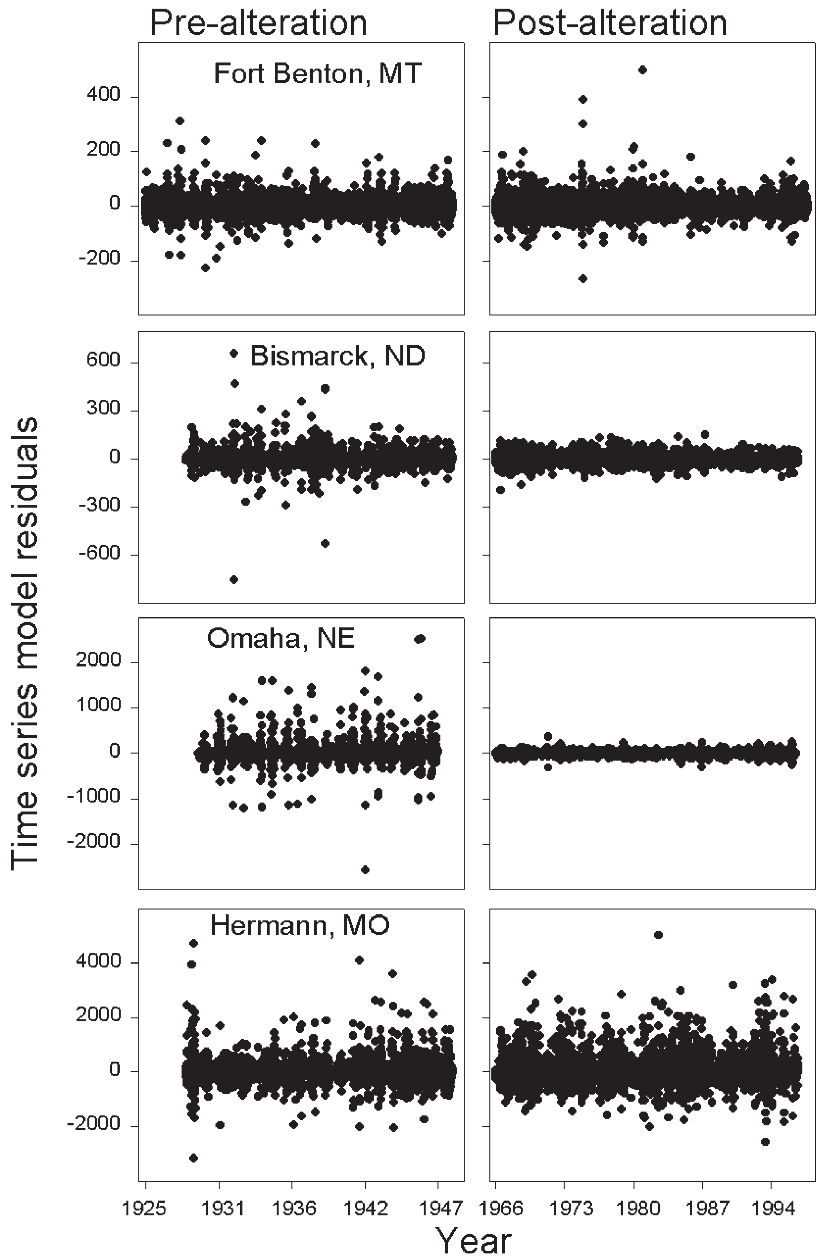

Figure 3. Pre-alteration and post-alteration residual plots from the autoregressive models for four representative gauges along the Missouri River.

tectable when looking at mean flows for each day over both periods of record (Fig. 4). Gauges located between reservoirs and the upper channelized zones show removal of the spring flood pulse in the post-alteration period.

Discussion

Our analyses show that Missouri River mean daily flows have significantly changed over time. These changes indicate that the nature of the daily mean flows have changed beyond the natural variation generally associated with annual or seasonal flow cycles between the two time periods. Additionally, variation was markedly reduced in the post-alteration period due to the regulation of flows from impoundments. Consequently, daily mean flows were significantly higher during the post-alteration period at all gauges when analyzed at the annual scale. There were also significant differences at the most strongly human-influenced gauges during the spring flow period (Table 2).

Many factors could have influenced the changes between these two periods, ranging from climatic shifts to water management practices. A shift in the amount of

Table 1. Summary of tests for differences in daily mean flows between pre- (1925–1948) and post-alteration (1967–1996) periods on the Missouri River, using data from the entire year. Gauges were tested individually. Percent change is the average difference in mean flow between periods (post-alteration – pre-alteration).

Gauge (USGS Gage #)	Period	Variance	*F*	*P*	Change (%)
Fort Benton, MT (06090800)	Pre: Post:	662641 522393	4.66	< 0.01	29
Wolf Point, MT (06177000)	Pre: Post:	424168 291058	3.79	< 0.01	43
Bismarck, ND (06342500)	Pre: Post:	21432690 1487294	10.08	< 0.01	16
Yankton, SD (06467500)	Pre: Post:	23953464 1194356	6.52	< 0.01	10
Omaha, NE (06610000)	Pre: Post:	18721078 5044982	10.74	< 0.01	34
Nebraska City, NE (06807000)	Pre: Post:	23154802 10794799	9.30	< 0.01	36
St. Joseph, MO (06818000)	Pre: Post:	35413740 38091531	8.57	< 0.01	39
Kansas City, MO (06893000)	Pre: Post:	48446994 54745238	5.31	< 0.01	43
Boonville, MO (06909000)	Pre: Post:	58861355 84368759	3.45	< 0.01	32
Hermann, MO (06934500)	Pre: Post:	100550000 130350000	1.91	0.03	36

Table 2. Summary of tests for differences in daily mean flow between pre- (1925–1948) and post-alteration (1967–1996) periods on the Missouri River, using data restricted to the spring spawning season (1 April – 30 June). Gauges were tested individually. Percent change is the average difference in mean flow between periods (post-alteration – pre-alteration).

Gauge (USGS Gage #)	Period	Variance	*F*	*P*	Change (%)
Fort Benton, MT (06090800)	Pre: Post:	2325883 2122792	0.32	0.93	2
Wolf Point, MT (06177000)	Pre: Post:	2958477 655288	0.62	0.25	14
Bismarck, ND (06342500)	Pre: Post:	52788478 2791839	2.53	0.02	– 32
Yankton, SD (06467500)	Pre: Post:	856161728 2768352	1.85	0.09	– 28
Omaha, NE (06610000)	Pre: Post:	54295925 10052889	2.04	0.06	– 5
Nebraska City, NE (06807000)	Pre: Post:	64983360 23629030	3.12	0.01	3
St. Joseph, MO (06818000)	Pre: Post:	88501831 74308764	2.91	0.01	7
Kansas City, MO (06893000)	Pre: Post:	140720000 112360000	2.18	0.04	6
Boonville, MO (06909000)	Pre: Post:	191390000 189090000	1.58	0.15	4
Hermann, MO (06934500)	Pre: Post:	360970000 339460000	0.61	0.72	7

annual precipitation entering the Missouri River basin could easily change daily mean flows between these two periods. Lower flow rates in the pre-alteration period may have resulted in the 1930s and 1940s when much of the United States, including the Missouri River Basin, underwent severe drought. Conversely, the 1990s were some of the wetter years on record for the Missouri River Basin. Hu et al. (1998) reported that the amount of annual precipitation generally declined from the 1880s through the mid 1960s and then began an upward trend in the lower Missouri River basin states of Nebraska, Kansas, and Missouri (Fig. 1). This change in annual precipitation, coupled with the managed water releases from the impoundments, seems a likely basis for the different daily mean flow values between the two periods in the lower portion of the river (Fig. 2).

The trend for higher precipitation rates does not persist throughout the entire basin however. Karl et al. (1996) reported that while the national trend over the past century has been for a slight increase in precipitation, the upper Missouri River states of Montana, Wyoming, and North Dakota (Fig. 1) have experienced a decline. This result conflicts with our finding of higher daily mean flows on an annual basis throughout the river system. Therefore, we must investigate other possible explanations on how and why daily flows are higher in the post-alteration period.

A possible explanation to higher post-alteration flows lies in river management strategies and their influence on long-term retention of runoff in the reservoirs. During a series of above average precipitation years, the reservoirs can fill to higher than mandated levels. Over a succession of several high precipitation years, the reservoirs may not be able to return to their prescribed winter pool elevations, thereby providing some carryover into following years. This carryover can lead to sustained higher flows and can temporally influence water release schedules beyond individual, annual climatic conditions. There is evidence to support this idea as post-impoundment period gauges that are heavily influenced by dam operations have exhibited annual variability that does not coincide with flow variability in other reaches of the Missouri River (Pegg and Pierce, 2002).

Because water is held back in each of the six mainstem reservoirs during spring flooding, we would expect the spring spawning flows in the inter-reservoir reaches and other areas influenced by dam operations to be lower than the pre-alteration period. Our findings support this prediction in that the Bismarck, ND, and Yankton, SD, gauges (Fig. 4) experienced a marked decrease in spring spawning flows during the post-alteration period. The Omaha, NE, gauge also experienced slightly lower spring fish spawning flows, indicating that the river is still influenced by reservoir operations roughly 250 km downstream of the last impoundment. However, moving downstream from these impoundments appears to mediate flow differences between the two periods due to inputs from relatively large tributaries (Galat and Lipkin, 2000; Pegg and Pierce, 2002). These tributaries are also regulated but to a lesser extent and not necessarily synchronous with Missouri River operations, thus providing additional variability.

Spring flows are important to the ecology of large rivers and is an area of strong concern when addressing biological problems throughout the Missouri River system (Galat et al., 1996). The flood-pulse concept (Junk et al., 1989) is based on the theory that biological communities in large floodplain rivers have evolved to utilize the timing, duration, and water level changes generally associated with spring flooding. These floods trigger fish spawning events, and provide food and nursery areas in addition to maintaining diversity within the system (Johnson et al., 1995). Therefore, basic biological functions such as spawning and recruitment may be curtailed, causing negative responses in diversity and density of native fishes due, in part, to the removal of flooding events as seen in the middle reaches of the river. Fish community information from the Missouri River suggests that species richness and abundances are much lower than would have been expected along a natural species gradient in the impoundment influenced reaches of the Missouri River compared to other reaches (Pegg, 2000). Consequently, our results reinforce the fact that it may be important to attempt to return the spring flow regime in the most affected areas to one resembling that of the pre-alteration period.

Analyses from studies investigating other aspects of flow on the Missouri River have generally reached the similar conclusion that the middle portion of the river has been most significantly altered (e.g., Galat and Lipkin, 2000). Using the IHA approach over a similar time period, Galat and Lipkin (2000) found that the relatively unaltered areas of the upper Missouri River, and to some extent the lower 600 km before joining the Mississippi River, maintained a certain degree of natural variability after impoundment, whereas the middle portion of the river was substantially altered. Coupling these findings with our study demonstrates a consistent trend in flow alteration that is most pronounced in the middle portion of the river. This trend could have a profound influence on how we view the river. Knowing that the middle portion of the river has undergone the largest impact from channelization and impoundment, research and flow mitigation efforts could be appropriately directed at this area to restore the hydrologic regime and also to protect, conserve, and rehabilitate biological communities.

There is little doubt that the Missouri River flow regime has changed between pre-impoundment and post-impoundment. Identifying the specific causes of these changes is clouded by the interaction of both natural phe-

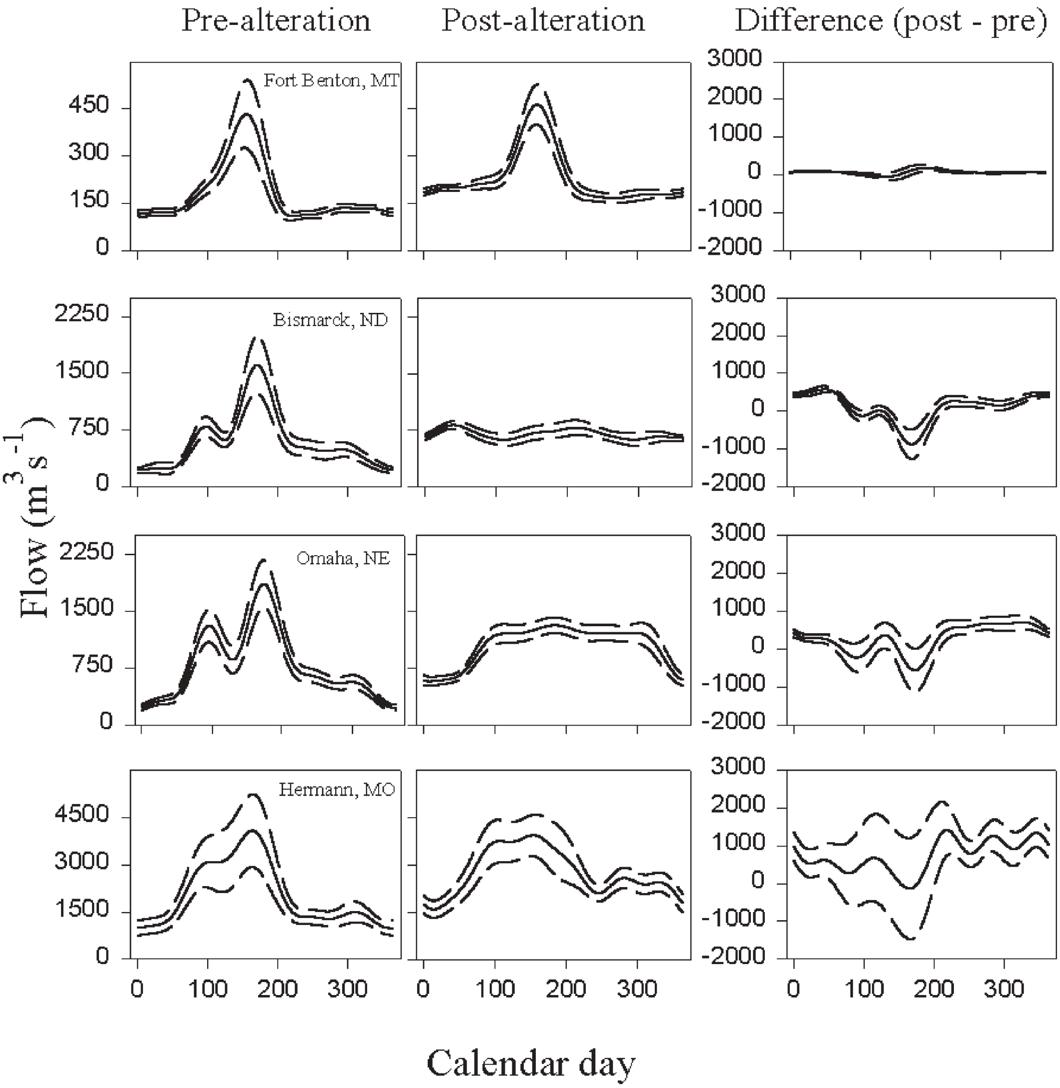

Figure 4. Mean flow for each calendar day over the pre-alteration (1925–1948) and post-alteration (1967–1996) periods at four representative gauges along the Missouri River. Dotted lines represent 95% confidence intervals. Spring spawning flows occurred from about day 90 to 180.

nomena and human alterations. Hydrology is not solely responsible for the structure of the biological community within this system, but it does play an important role and has been shown to delineate fish community structure and function in the Missouri River (Pegg, 2000). It is unlikely that the Missouri River will be returned to its pre-alteration state, partly due to the fact that not all of the changes are necessarily anthropogenic and partly because the multipurpose demands of the river for flood control, hydropower generation, navigation, irrigation, and recreation are given higher priority. However, providing a hydrograph similar to the pre-impoundment period at sites most greatly affected during spring flows may be a starting point to mediate some of the declining trends in aquatic and terrestrial communities now being reported along the Missouri River.

Acknowledgments

This research is a product of the Missouri River Benthic Fishes Consortium funded by the following federal agencies: Army Corps of Engineers (MOA PD-95-5832), Bureau of Reclamation, Environmental Protection Agency, Fish and Wildlife Service, and Geological Survey. Additional funding and logistic support were also received from the Iowa Department of Natural Resources, the Iowa Cooperative Fish and Wildlife Research Unit, and Iowa State University. We thank G. Atchison, D. Debinski, W. Meeker, J. Morris, and three anonymous reviewers for constructive comments on the manuscript. D. Dregnei and W. Fuller provided assistance with statistical and graphical analyses.

References

Berner, L. M., 1951. Limnology of the lower Missouri River. Ecology **32:** 1–12.

Box, G. E. P. and G. M. Jenkins, 1970. Time series analysis forecasting and control, Holden-Day, San Francisco, 553 pp.

Braaten, P. J., 2000. Growth of fishes in the Missouri River and lower Yellowstone River, and factors influencing recruitment of freshwater drum in the lower channelized Missouri River. Ph.D. Dissertation, Kansas State University, 174 pp.

Bravard, J. P. and G. E. Petts, 1996. Human impacts on fluvial systems. In G. E. Petts and C. Amoros (eds.), Fluvial Hydrosystems, Chapman & Hall, London, pp. 242–262.

Funk, J. L. and J. W. Robinson, 1974. Changes in the channel of the lower Missouri River and effects on fish and wildlife, Aquatic Series Number 11, Missouri Department of Conservation, Jefferson City, 52 pp.

Galat, D. L. and R. Lipkin, 2000. Restoring ecological integrity of great rivers: historical hydrographs aid in determining reference conditions for the Missouri River, Hydrobiologia **422/423:** 29–48.

Galat, D. L., J. W. Robinson and L. W. Hesse, 1996. Restoring aquatic resources to the lower Missouri River: issues and initiatives. In D. L. Galat and A. G. Frazier (eds.), Overview of river-floodplain ecology in the upper Mississippi River Basin, Volume 3 of J. A. Kelmelis (ed.), Science for floodplain management into the 21st Century, Washington, D.C., pp. 49–72.

Hesse, L. W., 1987. Taming the wild Missouri River: what has it cost? Fisheries **12:** 2–9.

Hesse, L. W. and G. E. Mestl, 1993. An alternative hydrograph for the Missouri River based on the precontrol condition. North American Journal of Fisheries Management **13:** 360–366.

Hu, Q., C. M. Woodruff and S. E. Mudrick, 1998. Interdecadal variations of annual precipitation in the central United States. Bulletin of the American Meteorological Society **79:** 221–229.

Ibanez, C., N. Prat and A. Canicio, 1996. Changes in the hydrology and sediment transport produced by large dams on the lower Ebro River and its estuary. Regulated Rivers: Research and Management **12:** 51–62.

Johnson, B. L., W. B. Richardson and T. J. Naimo, 1995. Past, present, and future concepts in large river ecology. BioScience **45:** 134–142.

Junk, W. J., P. B. Bayley and R. E. Sparks, 1989. The flood pulse concept in river-floodplain systems. Special Publication Canadian Journal of Fisheries and Aquatic Sciences **106:** 110–127.

Karl, T. R., R. W. Knight, D. R. Easterling and R. G. Quayle, 1996. Indices of climate change for the United States. Bulletin of the American Meteorological Society **77:** 279–292.

Ligon, F. K, W. E. Dietrich and W. J. Trush, 1995. Downstream ecological effects of dams. BioScience **45:** 183–192.

Morris, L. A., R. N. Langermeier, T. R. Russel and A. W. Witt, Jr., 1968. Effects of main stem impoundments and channelization upon the limnology of the Missouri River, Nebraska. Transactions of the American Fisheries Society **97:** 380–388.

Mosley, M. P., 1983. Variability of water temperatures in the braided Ashley and Rakaia Rivers. New Zealand Journal of Marine and Freshwater Research **17:** 331–342.

Oreskes, N., K. Schrader-Frechette and K. Belitz, 1994. Verification, validation, and confirmation of numerical models in the earth sciences. Science **263:** 641–646.

Pegg, M. A. and C. L. Pierce, 2002. Classification of reaches in the Missouri and lower Yellowstone Rivers based on flow characteristics. River Research and Applications **18:** 31–42.

Pegg, M. A., 2000. Hydrological variation along the Missouri River and its effect on the fish community. Ph.D. Dissertation, Iowa State University, Ames, 141 pp.

Petts, G. E., H. Moller and L. A. Roux (eds.), 1989. Historical change of large alluvial rivers: Western Europe, John Wiley & Sons, New York, 355 pp.

Poff, L. N., J. D. Allan, M. D. Bain, J. R. Karr, K. L. Prestegaard, B. L. Richter, R. E. Sparks and J. C. Stromberg, 1997. The natural flow regime: a paradigm for river conservation and restoration. BioScience **47:** 769–784.

Richter, B. D., J. V. Baumgartner, J. Powell and D. P. Braun, 1996. A method for assessing hydrologic alteration within ecosystems. Conservation Biology **10:** 1163–1174.

Richter, B. D., J. V. Baumgartner, R. Wigington and D. P. Braun, 1997. How much water does a river need? Freshwater Biology **37:** 231–249.

SAS Institute Inc., 1990. SAS/STAT user's guide, version 6. SAS Institute, Cary, North Carolina, 1848 pp.

SAS Institute Inc., 1991. SAS/ETS Software: Application Guide, Version 6, First Edition, SAS Institute, Cary, North Carolina, 264 pp.

Schneiders, B., 1996. The myth of environmental management: the Corps, the Missouri River, and the channelization project. Agricultural History **70:** 337–350.

Slizeski, J. J., J. L. Andersen and W. G. Dorough, 1982. Hydrologic setting, system operation, present and future stresses. In L. W. Hesse, G. L. Hergenrader, H. S. Lewis, S. D. Reetz and A. B. Wchlesinger (eds.), The middle Missouri River, The Missouri River Study Group, Nebraska, pp. 15–38.

Stanley, T. T. Jr., 1995. Ecosystem Management and the arrogance of humanism. Conservation Biology **9:** 255–262.

Ward, J. V. and J. A. Stanford, 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. Regulated Rivers: Research and Management **11:** 105–119.

Wei, W. W., 1990. Time series analysis. Addison-Wesley Publishing Company, New York, 478 pp.

Whitley, J. R. and R. S. Campbell, 1974. Some aspects of water quality and biology of the Missouri River. Transactions of the Missouri Academy of Science **8:** 60–72.

Yevjevich, V., 1984. Structure of Daily Hydrological Series, BookCrafters, Inc., Chelsea, 262 pp.