Enhanced stage and stage variability on the lower Missouri River benchmarked by Lewis and Clark

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ABSTRACT

Data from the 1803–1806 Lewis and Clark expedition and nineteenth century stage records are used to quantitatively benchmark natural, premanagement hydrology of the lower Missouri River and assess the magnitude and timing of hydrologic change over nearly two centuries. Data show doubling in daily stage variability from the nineteenth century to 2005. Annual maximum stages have, at some sites, become more extreme, and their seasonality is less regular. Observed changes adversely affect riverine habitat and flood levels; their timing, beginning as early as 1900, suggests that channelization is the major driver.

Keywords: basin management, Missouri River, hydrology, channelization, Lewis and Clark.

INTRODUCTION

Early twentieth century water projects are being reevaluated and management practices modified as knowledge of their long-term effects is obtained (Petts et al., 2000). On rivers where extensive engineering works predate scientific monitoring, restoration efforts are hindered by uncertainty about natural geomorphology and hydrology. Such is the case for the 3700 km Missouri River, which has been profoundly modified to minimize flooding, improve navigation, and supply water and hydropower. Unintended detrimental consequences include declining diversity of river basin biota, loss of wetland and sandbar habitat, and reductions in river sediment load (Funk and Robinson, 1974; Hesse et al., 1989). Enhanced flood levels have been linked to river constriction by levees and wing dikes (e.g., Criss and Shock, 2001), though debate persists on the relative contributions of climate variability and land-use change (e.g., Dyhouse, 1995; Miller and Nudds, 1996; Groisman et al., 2001). While qualitative descriptions of prealteration Missouri River hydrology abound (e.g., Browet, 1897), quantitative analyses conducted to date extend only from the late 1920s, postdating the first human-engineered changes by nearly a century (e.g., Galat and Lipkin, 2000; Pinter and Heine, 2005). We combine measurements made by Lewis and Clark with nineteenth century stage data sets to provide the longest available quantitative record of lower Missouri River hydrology. Using new relative stage techniques, the magnitude and timing of changes were tracked through four management periods. Expected hydrologic changes do not always correspond with observed changes. Dampened natural hydrologic variability, resulting from flow regulation by dams, is commonly blamed for ecosystem degradation (National Research Council, 2002). However, we find that stage variability has increased, not decreased, on the lower Missouri River and observe changes as early as 1900.

Missouri River management began in the 1820s with small local levee construction and removal of snags and bankside woodlands to facilitate boat traffic. In 1891, large-scale channelization began below Kansas City (Schneiders, 1999). Wing dikes that protrude from the river banks were installed, concentrating flow in the central channel. A 2.7-m-deep, 61-m-wide St. Louis–Sioux City navigational channel was complete by the early 1970s (Pinter and Heine, 2005). Between 1933 and 1963, six large main stem dams were constructed (Fig. 1). As a result, the river today has three ~1200 km sections with profoundly different hydrology: (1) the upper Missouri, which, aside from irrigation diversions, retains much of its natural character; (2) the middle Missouri, segmented by main stem dams and reservoirs; and (3) the flow-regulated lower Missouri, a single self-scouring channel maintained by dredging and wing dikes (Galat et al., 2005). This study focused on the lower Missouri River, where historical records are most complete and present river restoration efforts are focused. Water-use conflict, record floods in the 1990s, booming flood-plain development (Pinter, 2005), and ecosystem degradation prompt ongoing assessment of management practices.

METHODS

Lewis and Clark navigated a braided, sinuous Missouri River with rapids, sandbars, side channels, and extensive wetlands (Moulton, 2002). At their winter camps, they recorded daily change in river water level from 1 February to 14 May 1804 at Camp Dubois at the Mississippi-Missouri River confluence, and from 13 November 1804 to 7 April 1805 at Fort Mandan, now in North Dakota (Fig. 1). They also periodically surveyed river width. We compare these measurements to present values and use their water level change measurements to construct hydrographs (Table 1; Figs. 2A, 2B). Their efforts constitute the first quantitative hydrological study of the Missouri River and provide benchmark data for period I, the premanagement period.

Continuous records of daily stage—the ear-

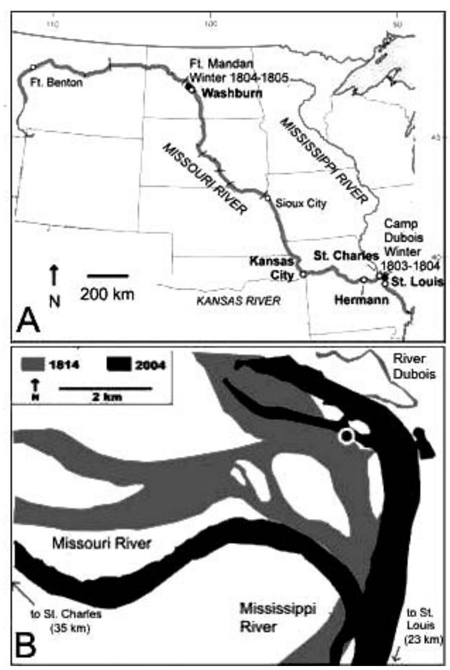

Figure 1. Missouri River basin. A: Sites of gauging stations used are indicated by open circles and bold text. Tick marks along river indicate main stem reservoirs on middle Missouri River, reach between upper Missouri River, upstream from Ft. Peck dam in eastern Montana, and lower Missouri, which refers to river below Gavins Point Dam, Sioux City, Iowa. B: Confluence of Missouri and Mississippi Rivers in 1814 and 2004 (after Harlan and Denny, 2003). Circle indicates Lewis and Clark's Camp Dubois, opposite mouth of Missouri River in 1804.

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TABLE 1. MISSOURI RIVER WIDTH AT PRESENT AND RECORDED BY LEWIS AND CLARK

Site	River (km)*		Width (m)		Date of L&C Measurement
	Present†	L&C§	Present†	L&C#	
St. Charles, MO	47	34	430	658	17 May 1804
Near Osage River	217	223	366	800	2 June 1804
Near Kansas River	591	586	302	457	27 June 1804

*Location from the mouth. L&C—Lewis and Clark.
†7.5' topographic quadrangles (U.S. Geological Survey, 1975, 1991, 1994).
§Dead reckoned estimates converted from imperial units (Moulton, 2002).
#Surveyed; converted from imperial units (Moulton, 1986–1987).

liest beginning in 1861—were compiled and analyzed for three subsequent periods (Missouri River Commission, 1886–1903; U.S. Department of Agriculture Weather Bureau, 1903–1928; U.S. Army Corps of Engineers [USACE], 2005a, 2005b; U.S. Geological Survey [USGS], 2005). These are (II) prechannelization, light management (1861–1890), (III) channelization-only management from 1910 to 1932, and (IV) the modern regime (1976–2004) of main stem reservoir release and channel maintenance. Gauging stations at St. Charles, Hermann, and Kansas City, Missouri, were used (Fig. 1). Modern data from St. Louis, just downstream of the Mississippi River confluence, and from St. Charles, just upstream of the confluence, best compare to the Camp Dubois data (Fig. 1B).

In this study, river stage was the best parameter for tracking hydrologic change. Stage is directly and easily measured, whereas daily discharge is calculated from stage, channel dimensions, and velocity profiles, and has uncertainties of 5%–15% (Wasklewicz et al., 2004). Moreover, stage quantifies the level of the water relative to landforms and directly affects riverine biota, especially sandbar availability, vegetation recruitment and regeneration, and habitat provision at specified depths. Records for stage are much longer than for discharge; there are continuous records from the 1870s. A complication is that historical changes in gauges, datums, and station locations are not always well documented. In our data set, pre-1898 and post-1898 stage datum conversions were unavailable. We circumvent this problem by investigating day-to-day changes in river stage and the difference of annual high stages (upper 2.5%) and low stages (lower 2.5%) from the annual median.

RESULTS

Hydrographs derived from Lewis and Clark's winter camp data feature mostly gradual daily changes and show an early spring rise (Figs. 2A, 2B). The Camp Dubois hydrograph features several curvilinear recessions following flood pulses, and the Ft. Mandan hydrograph includes rapid variations that correspond to the breakup of an ice dam (Moulton, 2002; Moody et al., 2003). Mean and standard deviation of daily changes in stage are 12.8 ± 13.3 cm and 10.4 ± 18.0 cm, respectively. These are upper limits, because data were discarded when the explorers recorded a tick mark, blank, or line, ambiguously denoting zero change or no measurement.

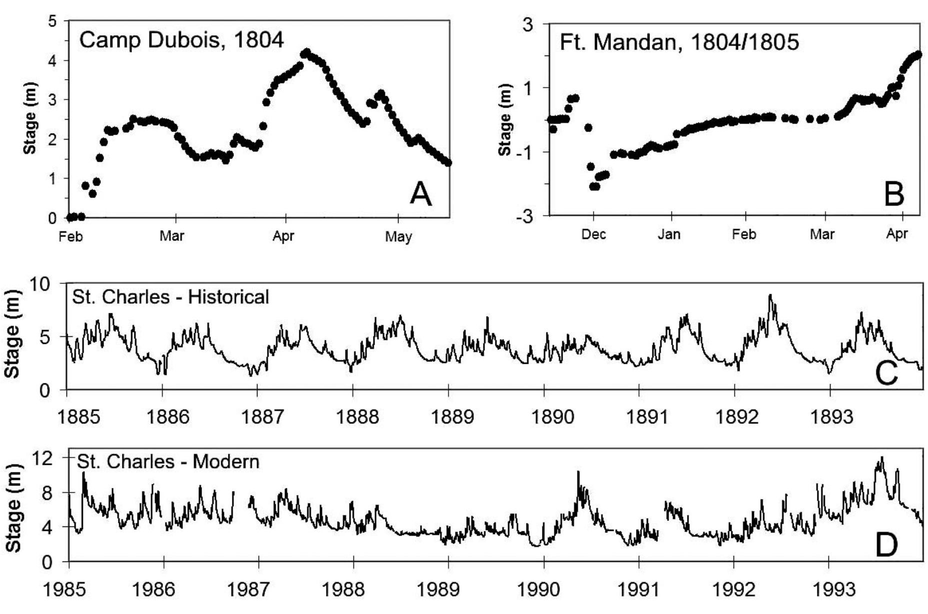

Figure 2. A, B: Hydrographs from Lewis and Clark water-level change data. Stage is relative to that on 1 February 1804 at Camp Dubois and 13 November 1804 at Washburn. C, D: Historical and modern stage hydrographs at St. Charles. Datums are not equivalent.

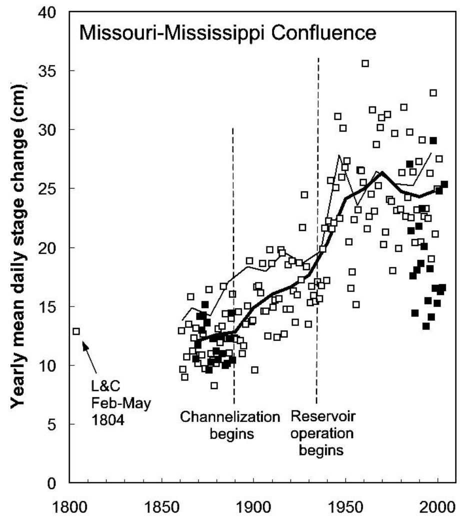

Figure 3. Annual mean daily stage change at St. Charles (filled squares) and St. Louis (open squares). Lines are 10 yr averages for all months (thick) and February to May only (thin), months in which Lewis and Clark (L&C) made measurements.

Daily stage changes in 1804–1805 are similar to those from the earliest subsequent records, ca. 1870 (Fig. 3), and prechannelization data show striking similarity along >1000 km (Table 2). Nineteenth century annual hydrographs are regular and periodic, typically with high stages in the spring and/or summer. Most modern hydrographs differ profoundly and show numerous irregular spikes in river stage throughout the year and reduced annual periodicity (Figs. 2C, 2D). We characterized this "flashiness" on daily and annual time scales.

Daily stage change increased over the twentieth century at all sites investigated (Table 2). Similar trends are evident from Kansas City to St. Louis in spite any of potential site-specific influences. Modern mean daily stage changes are nearly two times greater than historical values and have larger standard deviations.

Annual high stages relative to the median increased over time at two stations but were unchanged at Kansas City. Standard deviation and variability in timing have increased at all stations. Most annual highs still occur in spring and summer but on average are 5–38 days earlier than in period II; fall and winter high stages are now common. No clear trends are evident for low stage magnitude, but seasonality has changed, with lows tending to occur slightly later in the winter.

DISCUSSION

Mean annual daily stage change began to increase ca. 1900 (Fig. 3; Table 2), grew

TABLE 2. SUMMARY OF STAGE VARIABLE STATISTICS

Site (number of values) (N_I, N_{II}, N_{III}, N_{IV})	Time period (mean ± standard deviation)				Significance (p values)*					
	I	II	III	IV	I-II	I-III	I-IV	II-III	II-IV	III-IV
Daily Change (cm)†										
Camp Dubois (91)	12.8 ± 13.3						compared to St. L. and St. C.			
St. Louis (–, 10,980, 8,418, 9,516)	–	12.2 ± 15.8	16.8 ± 20.8	24.5 ± 27.0	0.16	0.2	<**0.001**	<**0.001**	<**0.001**	<**0.001**
St. Charles (–, 4,392, –, 7,320	–	12.3 ± 15.6	–	19.2 ± 25.9	0.18	–	**0.04**	–	<**0.001**	–
Hermann (6,222, 8,418, 10,248)	–	12.7 ± 22.3	15.1 ± 19.8	21.2 ± 29.0	–	–	–	<**0.001**	<**0.001**	<**0.001**
Kansas City (6,588, 8,418, 10,248)	–	9.6 ± 12.9	13.7 ± 17.7	15.5 ± 25.5	–	–	–	<**0.001**	<**0.001**	0.17
Ft. Mandan (96)	10.4 ± 18.0	–	–	–	–	–	–	–	–	–
High Stage (rel. to median, cm)†										
St. Charles (–, 118, –, 180)	–	308.6 ± 104.2	–	392.2 ± 108.5	–	–	–	–	<**0.001**	–
Hermann (–, 142, 227, 278)	–	276.4 ± 76.5	341.8 ± 88.1	452.2 ± 108.8	–	–	–	<**0.001**	<**0.001**	<**0.001**
Kansas City (–, 167, 230, 277)	–	324.0 ± 78.5	325.8 ± 89.5	325.3 ± 125.9	–	–	–	0.54	0.75	0.98
Low Stage (rel. to median, cm)†										
St. Charles (–, 118, –, 180)	–	199.6 ± 51.5	–	174.4 ± 45.0	–	–	–	–	<**0.001**	–
Hermann (–, 142, 227, 278)	–	198.2 ± 58.2	172.1 ± 40.4	188.3 ± 59.8	–	–	–	<**0.001**	0.15	**0.006**
Kansas City (–, 167, 230, 277)	–	161.4 ± 42.3	176.0 ± 42.2	180.8 ± 58.2	–	–	–	**0.0012**	**0.002**	0.43
High Stage Seasonality (day of year)§										
St. Charles	–	155 ± 40	–	131 ± 57	–	–	–	–	<**0.001**	–
Hermann	–	163 ± 36	159 ± 60	125 ± 68	–	–	–	<**0.001**	<**0.001**	<**0.001**
Kansas City	–	163 ± 32	157 ± 49	158 ± 56	–	–	–	<**0.001**	<**0.001**	<**0.001**
Low Stage Seasonality (day of year)§										
St. Charles	–	350 ± 21	–	359 ± 36	–	–	–	–	<**0.001**	–
Hermann	–	352 ± 31	357 ± 30	6 ± 32	–	–	–	<**0.001**	<**0.001**	<**0.001**
Kansas City	–	356 ± 24	357 ± 21	9 ± 19	–	–	–	<**0.001**	<**0.001**	<**0.001**

Note: – indicates no data available.

*Values are boldface when significant at the $p < 0.05$ level.

†For comparisons involving only periods II-IV, the Mann-Whitney U test was used. Because the sample of period I was very small compared to modern samples, the one-sample z-test was used. Modern absolute daily stage change values were converted to normal distribution via square root transformation, and period I values were tested against "population" means and standard deviations from periods II-IV.

§The Watson's U^2 circular statistic was used to test equality of distributions. It is sensitive to differences in both means and distributions.

steadily until ca. 1950, and thereafter remained high and variable. These changes cannot be explained by small (<5 cm) improvements in gauging instrument sensitivity since 1890. Instead, the period of increase in daily stage change corresponds with the period of intensive channelization that began in 1891. Post-1950 stabilization of daily stage change corresponds to the onset of operation of large main stem reservoirs.

Management-hydrologic change correlation alone cannot establish cause. Volumetric river discharge is $Q = Av$ or $Q = wv(h - h')$, where the parameters are the cross-sectional area (A), channel width (w), average velocity (v), stage elevation (h), and channel bed elevation (h'). Daily changes in h', w, and v are expected to be rather small, so stage change over short intervals is $dh \sim dQ/(w \cdot v)$. If increased daily stage change were primarily due to changes in flow (dQ), either from reservoir release, land-use change, or meteorological changes, a complementary trend in daily discharge change would be expected. No such trend is evident in the post-1929 discharge record available for examination (USGS, 2005).

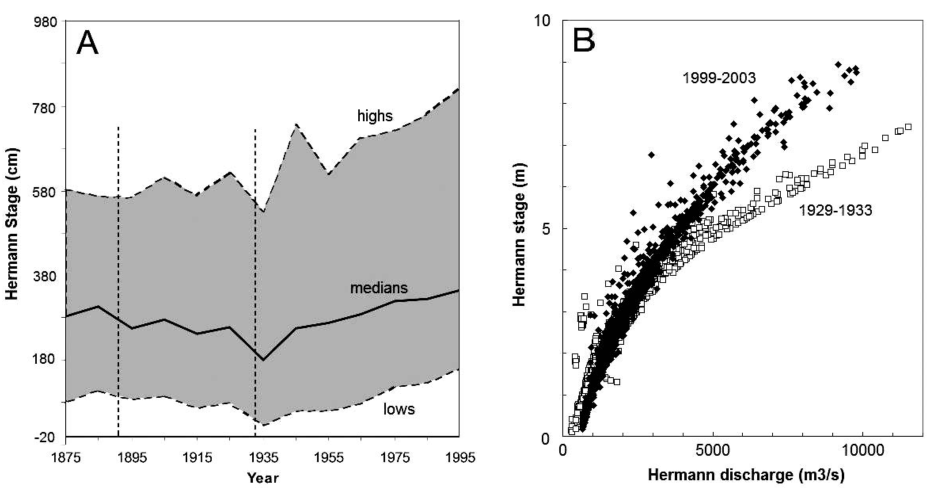

Figure 4. A: Time series of decadal averages of high, median, and low stages at Hermann, Missouri. Dashed lines refer to onset of channelization and reservoir management activities, respectively. B: Hermann stage vs. discharge rating curves.

Seasonality changes in high and low stages are likely due to reservoir releases. Increasing differences between annual high stages and annual median stage could reflect an increase in the former or a decrease in the latter. At Hermann, we can reconstruct absolute stage to within ~10 cm accuracy. The pre-1898 datum was converted by setting the 31 December 1897 measurement equal to that from 1 January 1898. Fluctuations over 3 prior and subsequent days were 10 and 0 cm, respectively, so introduced error is likely small. After initial decline in median stages (but not high stages) corresponding to the onset of channelization (Fig. 4A), median stages began to increase in the 1930s and are clearly not due to increased flow. Stages were higher in 1998–2002 than in 1928–1933 for equivalent discharges (Fig. 4B), in agreement with similar findings by Criss and Shock (2001) and Pinter and Heine (2005).

The simplest explanation for all observations is systematic change in the engineered channel cross-sectional profile. The lower Missouri River is only one-half to two-thirds as wide as it was in 1804–1805 (Table 1). Other things being equal, this narrowing would account for a doubling in daily stage fluctuation and higher stages. Dyhouse (1995) hypothesized that scour and increased flow velocity compensate for loss of width when wing dikes are installed, resulting in unchanged or lowered stages. Hermann, Missouri, data show this may have been the case initially, but is no longer true. River adjustment since 1930 has driven low, median, and high stages upward at Hermann by 1–2 m or more. Similar changes are observed at St. Charles but not at Kansas City, where engineering works to combat channel degradation (Jacobson and Galat, 2006) are ongoing.

CONCLUSIONS

Increased stage variability and higher stages on the lower Missouri River decrease flood recurrence intervals and have diverse implications for management and flood-plain development. Reservoir release far upstream is not the most important hydrologic control; stage parameters were altered before reservoir construction. Contrary to the assertion of ''substantial reductions in the daily and annual variability of hydrologic and geomorphic processes'' (National Resource Council, 2002, p. 1), we find that management on the lower Missouri River has increased stage variability. Ecosystem restoration proposals (USACE, 2004) focus on optimizing seasonal reservoir releases to simulate a more natural hydrologic regime. Our results show that parameters related to channelization deserve greater attention as they drive observed stage variability increases and control stability intervals required for habitat provision (Poff et al., 1997).

The Missouri River may be particularly affected by channelization because of naturally high interannual variability of its basin drainage. For example, during the past 65 yr, daily mean streamflow at Hermann, Missouri, varied from 118 m^3/s (11 January 1940) to 20,900 m^3/s (31 July 1993). The river's oversized natural channel, a product of dramatic flow variations in the Pleistocene, has been narrowed, increasing water depths during minimum flows to allow navigation but reducing the ability of the channel to carry high discharges. Scour has not compensated for width decreases, and the net result is both higher stages and increased stage fluctuation. Currently planned flow regime management will not ameliorate these particular effects. We suggest that widening the river in selected reaches to reconnect it to its floodplain, i.e., restoring width, would have a triple benefit by reducing flood stages, decreasing the magnitude of short-term stage fluctuations, and providing additional shallow-water habitat for river biota. An active channel expansion program is under way on another major world river, the Rhine (e.g., Nienhius et al., 2002). A smaller-scale program was implemented on the lower Missouri River following the 1993 floods. Breached levees were left unrepaired in select areas to create a string of protected areas with bottomlands reconnected to river hydrologic fluctuations. Work at one such area, Jameson Island, shows that more natural channel morphology has increased availability of shallow-water habitat, in spite of a still largely irregular flow regime (Jacobson and Galat, 2006). Thus, river widening may be an effective tool for ecosystem management of large rivers and might enable selected stretches of the lower Missouri River to function more like those traversed by Lewis and Clark.

ACKNOWLEDGMENTS

We thank J. Boardman, M. New, and R. Rotman for helpful reviews and J. Keirstead for discussion of statistics. D. Cribs (library, University of Missouri, St. Louis) and personnel at the state and regional offices of the U.S. Geological Survey and Army Corps of Engineers were of invaluable help in obtaining historical records. Ehlmann was partially supported by the Rhodes Trust and Keble College.

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Manuscript received 23 February 2006
Revised manuscript received 11 June 2006
Manuscript accepted 17 June 2006

Printed in USA