Hydrologic History
of the Lower Missouri River

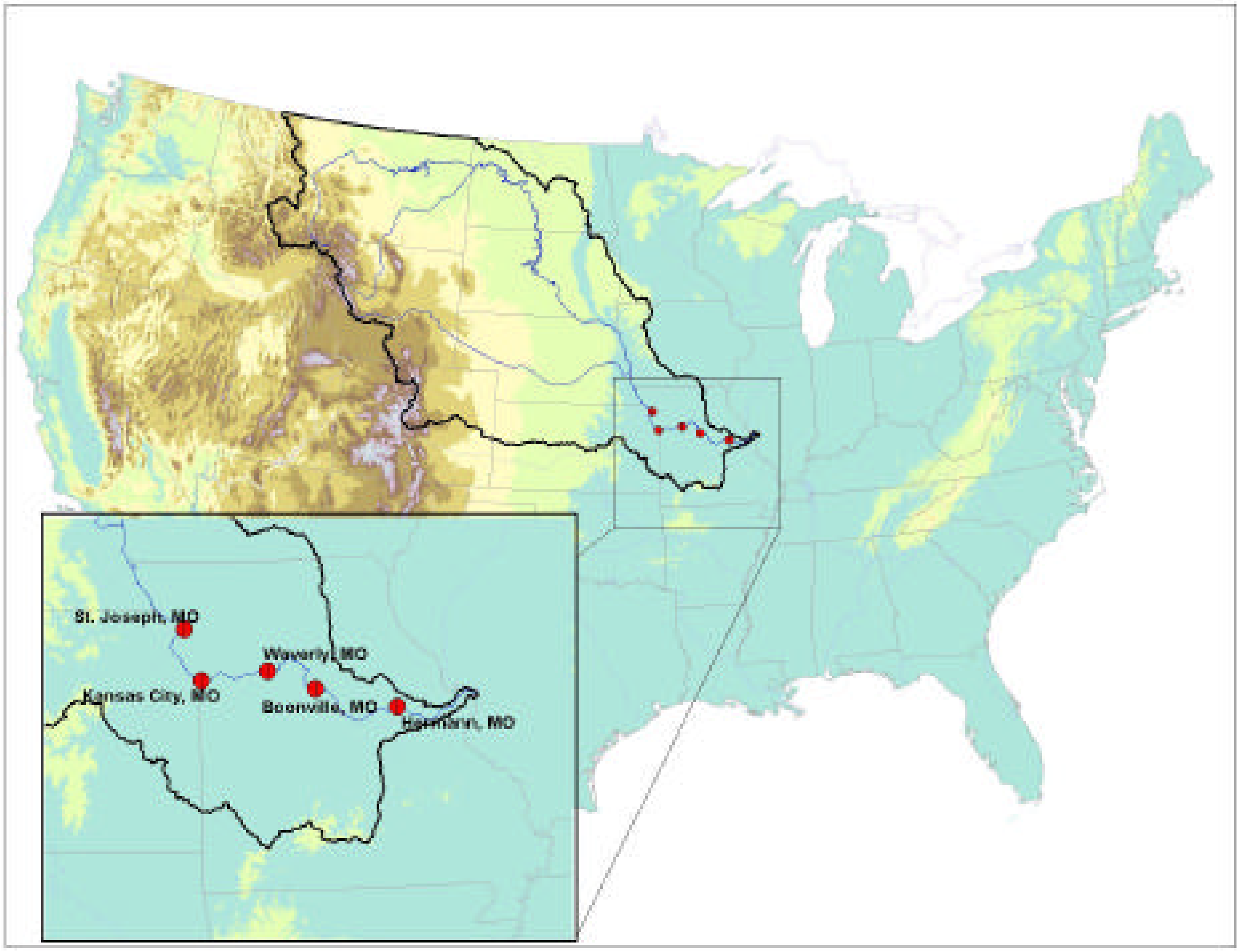

Fig. 1. The Missouri River basin and study sites along the Lower Missouri River.

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EXECUTIVE SUMMARY

The goals of this research were to (1) document long-term trends in flow conveyance on the Lower Missouri River (LMoR), (2) begin to assess what mechanisms have caused these trends, and (3) update flood frequencies using the new “stage indexing” technique.

Five stations along the LMoR were examined using specific–gage analysis (SGA), which is a technique that holds discharge constant in order to observe trends in a parameter such as stage over time. This analysis reveals that for all flood conditions on the LMoR, stages have systematically risen for equal discharge volumes over the period of record. SGA can also be used for analyzing other time-series parameters such as cross-sectional area, flow velocity, or channel width, which illustrate the actual mechanisms of channel change. The results show that at three LMoR stations, velocity appeared to be the dominate mechanism driving shifting stage changes. At the two other stations studied, constriction in channel cross-sectional area appear to have driven increases in flood stages.

Rising flood stage trends imply that large floods will occur more frequently than previously estimated. The stage indexing technique updates flood frequencies by incorporating long-term stage trends in order to homogenize historical stage data to the current year. Using this technique, estimated frequencies for all large flood events at all five LMoR stations analyzed were increased, sometimes dramatically. For example at Boonville, the largest flood occurring in the 70-year record was the 1993 flood with a stage of 35.16 ft. Without accounting for the long-term shifts, the 1993 flood would have a recurrence interval of at least 71 years, and recurrence times of 100-500 years are commonly cited. After indexing, however, the 1993 flood drops to just the 4th largest flood by stage, and the adjusted recurrence interval for a stage of 35.16 ft drops to 15-20 years under present-day conditions.

Such profound changes in flood response should be recognized on the Missouri River and incorporated into current estimates of flood hazard and into strategies for river management and flood mitigation.

BACKGROUND AND PROBLEM DESCRIPTION

According to a recent National Research Council panel, "there are ... few cases where human impacts on flood magnitude and frequency have been carefully documented" (National Research Council, 1999). Although some authors assume that human activities have been proven to magnify downstream flooding, many engineers and planners dismiss evidence for rising trends and deny any smoking-gun evidence for specific human contributions. Following the 1973 flooding on the Mississippi River, two studies suggested that this event represented the culmination of a trend of rising flood stages as a result of levees and other river engineering structures. Although still widely cited in the environmental literature today, each of these studies had serious methodological limitations, and both have been largely ignored in the engineering literature. Challenges in documenting human magnification of flooding include: (1) separating long-term trends from short-term hydrologic variability; (2) quantifying the contributions of climate, land-use shifts, and river engineering; and (3) incorporating hydrologic shifts into flood-frequency calculations.

New statistical techniques, however, now allow reanalysis of the assertion of systematic increases in flood heights and the role of river engineering in causing these increases. An intensive pilot study (Pinter et al., 2000; Pinter et al., 2001) focused on the portion of the Mississippi River between the Ohio River and Missouri confluences (the so-called Middle Mississippi River, or "MMR"), which includes the St. Louis metro area. Unlike previous studies which looked only at raw data, this research utilized the specific-gage technique, which is a powerful statistical tool for reducing scatter in hydrologic time series and for limiting the number of independent variables. Analysis of the three long-duration stations on the MMR (St. Louis, Chester, Thebes) reveals the same historical trends all along this river reach. For the lowest discharges, of no interest to flood hazard, stages have declined over time. This is understood to be the result of bed incision and accelerated flow velocities resulting from channel constriction. For larger discharges, however, flood stages have systematically increased over the duration of record. This means that equal and unchanging quantities of runoff (the nature of the specific gage) resulted in higher and higher flood stages. For example, whereas the 20,170 cms (712,200 cfs) flood of 1861 caused a river stage of 9.60 m (31.5 ft) at St. Louis, the same quantity of water would have resulted in a flood of approximately 12.6 m (41.2 ft) in 1999.

STUDY AREA

From its headwaters in the Rocky Mountains, the Missouri River (Figure 1) runs over 2500 miles (4000 km) to its confluence with the Mississippi River just upstream of St. Louis. The Missouri River drains an area of 530,000 mi^2 (1,370,000 km^2) which far outstrips the basin of the Mississippi above the confluence, at just 170,000 mi^2 (440,000 km^2). In terms of both river length and basin area, the Upper Mississippi River could be considered a tributary to the Missouri. The Missouri River basin has an average elevation of about 1300 ft (400 m), average annual precipitation of about 12 in (30.5 cm), and mean annual temperature of 38°F (3°C; Maher, 1964).

The Missouri River was first seen by people of European descent in 1673. In can be argued that, from the river's point of view, the history since then has been all downhill. The Missouri has been sweepingly transformed, primarily during the past century, from a wide, relatively shallow and highly dynamic mobile system to a intensively engineered channel, primarily in order to facilitate riverboat navigation. The focus of this work has been the Lower Missouri River, which is the portion of the river downstream of Gavins Point Dam. Gavins Point Dam represents the last of the five mainstem impoundments that have transformed much of the Upper Missouri into a series of standing lakes. In contrast, engineering modifications of the Lower Missouri have focused on constricting and straightening the channel in order to maintain minimum navigation depths, armoring of the banks to prevent lateral erosion, and construction of levees to exclude flood flows from the floodplain. An outline of the major legislative, engineering, and natural events that have shaped the Lower Missouri is presented in Table 1.

TABLE 1. OUTLINE HISTORY OF THE LOWER MISSOURI RIVER

1673	Missouri River first seen by Europeans
1804	Lewis and Clark expedition
1824	preliminary snagging by Army Corps of Engineers
1844	1844 flood, 12-17 ft above bankfull
1856	Steamship reaches Sioux City
1860	Steam ship reaches Fort Benton, Montana
1880	"Suter" plan for improving the Missouri
1880s	"boom years" of navigation on the Missouri
1881	1881 Flood, 3ft above 1844 crest at St. Joseph
1884	Missouri River Commission (MoRC) established
1887	railroads reach Fort Benton
1902	River and Harbor Act abolishes the MoRC
1903	1903 Flood; 14 ft above bankfull at KC
1907	River and Harbors Act: $450,000 for maintenance, survey to Sioux City
1908	1908 Flood; 9 ft above bankfull at KC
1910	River and Harbors Act: $1M for 6-ft channel, Sioux City to mouth
1912	100,000 ft of revetment, 4500 ft of dikes under constr.
1913	project 44% complete
1914	WWI breaks out, work suspended shortly
1915	Upper Camden Bend cutoff (Mi. 340)
1915	10-yr timetable questioned, project rexamined
1915	River and Harbors Act: lays out cost-share: 25% local contribution
1926	"House Document 308" system-wide study
1927	Congress: 6-ft channel ext. to Sioux City, $12M
1927	River and Harbors Act: study feasibility of 9-ft channell to KC
1929	$40M spent on 6-ft channel, 55% regulated to KC
early 30s	drought years
1932	House Document 238, Missouri River flooding overview
1935	regulation 75% complete, KC to Rulo, NE
1935-6	Congress $3.3B to public works, incl. navigation
1936	Flood Control Act: $10M for KC levees and walls
1938	Flood Control Act: 5 dams on Kansas R. tribs.
1940	Big Blue Bend cutoff
1941	WWII begins, most work suspended river at St.Joseph returned to "wild state"
1943	1943 Flood
1945	Pick-Sloan Plan enacted; authorizes a 9-ft channel, KC to the mouth ulimately would cost ~$1B
1947	1947 Flood: records set at Rulo, St.Joe, Waverly
1948	1st Pick-Sloan levee, L-488 at St.Joseph initiated
1949	Liberty Bend cutoff
1951	"Great Flood" of 1951 focuses on Kansas; Kansas City River 4-6 ft above KC levees downstream: "every ag. Levee breached"
1952	1952 Flood almost equals 1881 record at St. Joseph; natural cutoff strands city
1955	L-488 completed
1958	Water Supply Act: added water supply to dam "benefits"
1961	9-ft channel 91% complete (but only 7ft passable)
1963	250,000 (of 400,000) floodplain acres within Federal Levees
early 70s	9-ft channel complete, except at crossings (~8 ft) 20% of levee projects completed, = 200 levee miles
1993	great Midwestern Flood

Modified after Branyan, 1974.

DATA

Historical hydrologic data was collected for five long-term gaging stations on the Lower Missouri River: at St. Joseph, Kansas City, Waverly, Boonville, and Hermann (see Fig. 1). Systematic records have been kept at these stations since at least 1930, providing 70+ years of continuous monitoring. Daily measurements of river stage were obtained from the U.S. Army Corps of Engineers, and corresponding estimates of daily discharge were obtained from the U.S. Geological Survey. In addition, summaries of the channel gaging measurements at each stations were also available from the U.S. Geological Survey, consisting of width, average depth, and average flow velocity recorded approximately biweekly but as frequently as daily during recent floods. All data were checked for continuity and quality and corrected for any changes in gage location or datum elevation. A small but significant number of values were erroneous or otherwise required attention. For each station, complete time series of stage, width, depth, and velocity were tabulated. Any one-day change of more than +/- 5% was flagged, and if discharge did not change by a comparable amount, then the value in question was removed from the data set. Gage histories at each station were examined, and any changes in datum elevation were noted and used to correct all stage data to a uniform frame of reference.

METHODS

The research outlined here consisted of three principal methodological steps: (1) specific gage analysis, (2) equi-discharge analysis of cross-sectional parameters, and (3) stage indexing.

Specific-Gage Analysis

The specific-gage technique (Blench, 1969; Biedenharn and Watson, 1997) utilizes daily stage and discharge data to test for long-term changes in the stage-discharge relationship of a river at a given cross section. For each year of data, an annual rating curve is constructed. Each rating curve is constructed by plotting stage against log of discharge using all of the daily data for a given calender year. A regression is then fit to each year’s rating curve; our experience has shown that second-order polynomial fits on log of discharge result in the best fits, but alternatives will continue to be tested. The time-series of annual rating curves are then used to track stage shifts associated with any preselected quantity of water. For each year, the regression equation is used to calculate the stages associated with the chosen discharge or discharges. Experience has also shown that extrapolating the regression beyond the measured range in a given year creates unacceptable error; as a result, it is recommended that no stage be calculated for discharges less than the measured minimum for that year or more than the measured maximum. If the r^2 value for a given year is 0.95 or less or if there is a visible anomaly in the rating curve, those data will be reexamined manually. The final step in this procedure is to plot the stages associated with a fixed discharge from all the years against time for each gaging station of interest.

The principal advantages of the specific-gage method are that: 1) it utilizes a far greater density of data (daily measurements) than any technique using only annual data (e.g., the “time-trend analysis” of Belt [1975]), 2) it dramatically reduces scatter by calculating an average annual stage value for a particular discharge, 3) it tracks stage trends for precisely the same discharge rather than simply the largest or smallest value in a given year, and 4) any changes over time thus identified are necessarily linked to the conveyance capacity of the channel at or near the gage. Specific-gage analysis of historical data reveal stage trends with very little scatter and free from many of the causal ambiguities in some previous work.

Cross-Sectional Analysis

When limited to stage changes associated with a fixed discharge, and with upstream changes in the river channel and contributing basin excluded, the mechanisms that may have caused the Lower Missouri's altered flood response are fairly limited. Discharge (Q) at a cross section is:

$$Q = w \cdot d \cdot v \tag{1}$$

where w is channel width, d is average depth, and v is average flow velocity. Channel depth is the sum of stage (h; gage datum to water surface) and the average depth from the datum down to the channel bed (d'), so that:

$$Q = w\,(h + d')\,v \tag{2}$$

Solving for stage:

$$h = Q/(w \cdot v) - d' \tag{3}$$

With discharge held constant, there are just three possible direct causes of increased stage over time: 1) decreased width, 2) decreased hydraulic depth, or 3) decreased velocity.

A new tool has been developed for testing which combination of the three possible causal mechanisms above are responsible for a rising or falling specific gage. This tool takes advantage of channel cross-sectional measurements compiled at stations gaged by the USGS: channel width, cross-sectional area, and average velocity. To identify erroneous data, each parameter at a given station was plotted against discharge, and clear outliers on these graphs were removed. As with the analysis of stage data over time, the cross-sectional values were separated by year, and each year's cross-sectional variable plotted against log of discharge. A regression was calculated for each yearly relationship. For all years with an r^2 value of 0.90 or greater, the equation for the best-fit line was used to generate a value for the variable associated with a given discharge. The end result was a history of channel geometry and flow velocity for each cross-sectional parameter at each measurement station, which can shed valuable light on the causes of changes in flood behavior.

Stage Indexing

Historical hydrologic records are used to determine future flood probabilities, recurrence times, project-flood heights, and zoning regulations. Given systematic patterns of long-term stage increases on a river, damaging floods can be expected to occur with increasing frequency, and design floods of a given recurrence can be expected to be higher than calculated using out-of-date predictions or using methods that do not incorporate these trends. The very fact that stages vary over time demonstrates non-stationarity and seems to disqualify this data set from use in flood-frequency analysis. However, this obstacle can be overcome if the data can be statistically homogenized and analyzed as a single population. Homogenization removes the variance in stage attributable to time, allowing comparison of all stage data under comparable conditions – the most obvious being to homogenize to the present-day. For all three stations along the MMR study reach, the specific-gage plots were linear at the 95% confidence level over the range of discharges shown. (Extreme discharges at both the high and low ends lose significance as points drop out because of the "no extrapolation" rule applied.) Because the stage trends for the MMR stations are linear, the preliminary system developed here is one of "linear indexing". However, more complex non-linear approaches may well be more appropriate for other river reaches, and these are discussed below. Using linear indexing, the indexed stage (h_I) corresponding to a historical flood with a measured stage of h that occurred in year j, indexed to year k can be expressed as:

$$h_I = h + (k - j)dh/dt \tag{4}$$

where dh/dt is the rate of stage change over time in m/yr for the measured discharge of that flood. Rates of stage change were calculated for discharges at 40,000 cfs increments for each station. Within these increments, the rates of stage change were interpolated to the measured discharge values. Historical maximum annual stages were indexed to 2001 for all five stations for the duration of the record.

RESULTS

Specific-Gage Analysis

Results of the specific-gage analyses for the five Lower Missouri River stations are shown in Figures 2 to 11 of Appendix I. At each station the trends in stage over time depend on the discharge. For the lowest flows, the associated stages trended systematically downward. The same pattern was observed on the Mississippi River and was ascribed to the effects of incision and increased conveyance due to channel constriction (Pinter et al., 2000). For larger discharges, however, the opposite pattern was observed – the stages associated with fixed quantities of water rose systematically over the durations of record at all the stations. The cross-over discharges, at which falling stages changed to rising stages, occurred at 36%, 39%, and 37% of bank-full flow at Hermann, St. Joseph, and at Boonville, respectively. At Waverly, no falling stages were observed, only rising trends. In contrast, at Kansas City, the cross-over discharge was much higher, at about 100% of bank-full flow. This means that at Kansas City, all within-channel flows were conveyed more efficiently over time, whereas all flood flows – like at every other station – resulted in higher and higher stages over time for the same quantity of water. The likely causes of both rising and falling trends, as well as the significance of the cross-over discharge at each station, will be discussed in the following section.

The stage changes at different discharge conditions and at different stations can be compared easily using what we call a “specific-gage summary diagram” (Figures 3, 5, 7, 9, and 11). This type of diagram plots the average rate of stage change (positive for increasing; negative for decreasing) vs. the range of discharges analyzed, and it illustrates the stage reductions for low flows (points below the zero line), the cross-over discharge for each station, and the stage increases for larger in-channel and flood flows. Because our specific-gage approach plots a point for a given discharge for a given year if and only if that discharge actually occurred in that year, the number of data points diminishes rapidly for extremely large or extremely small discharges. The number of observations are plotted for each discharge here to help explain some sudden jumps in the summary diagrams, which usually correspond to the loss of large chunks of the record for particular discharges.

As observed on the Middle Mississippi River just downstream (Pinter et al., 2001), the specific-gage trends on the Lower Missouri River are roughly linear over the ~70 year duration of record. At the same time, significant short-term deviations from the long-term linear trends stand out as more than just year-to-year variability at the five stations analyzed. In particular, at all the stations except Waverly, flood stages rise dramatically in the first decade or so of record, with only more modest increases thereafter. This pattern is clearest at Boonville, where the 300,000 cfs points on Figure 4 can be seen to rise about 7 ft between 1927 and 1935, with only about 5-6 ft of additional increase in the following ~60 years. That initial increase is evident down to about 180,000 cfs but clearly is not present for the smaller, within-channel flows. The possible significant of this observation is discussed in the following section.

Cross-Sectional Analysis

Results of the analyses of cross-sectional measurements at each of the five Lower Missouri River stations are shown in Figures 12 to 21 of Appendix II and Figures 22 to 26 of Appendix III. Figures 12-21 show trends over time in cross-sectional area and in average flow velocity for equal discharge conditions. Measured channel width was also derived from the data at each station, but the relation between width and discharge (the “width rating”) proved to be much less linear than for any other parameter analyzed, so that there was a large degree of interannual variability, and the specific-width results were deemed not trustworthy.

As outlined above, there are just three possible causes of rising stage trends for equal discharges: 1) decreased width, 2) decreased hydraulic depth, or 3) decreased velocity. For the five Lower Missouri River stations, two patterns in the cross-sectional analyses were observed: (1) trends in flood stages driven by flow deceleration, and (2) trends in flood stages driven by cross-sectional-area reduction. First, flood magnification by velocity loss was evident at Boonville, Kansas City, and St. Joseph. At the latter two stations, decreasing velocities over time drove flood stages higher in spite of fairly significant <u>in</u>creases in cross-sectional area, a change that by itself would tend to drive stages downward. Second, at Hermann and Waverly, flow velocities trended slightly higher at all discharge conditions, but this flood-lowering effect was overwhelmed by the much larger influence at those stations of channel cross-sectional area loss. Boonville experienced both the deceleration of flow velocities over time as well as area loss for the largest discharges, which helps to explain why it exhibits the most severe magnification of flood risk in the following section (Results of Stage Indexing).

Because, as discussed two paragraphs above, specific-width analysis was considered unreliable, these observations were not subdivided into the results of channel constriction (reduced width) and channel shallowing (reduced depth). In order to distinguish these two possibilities, the bed elevation of the channel at each station was derived from the data by subtracting the average channel depth on a given day – which is equal to the measured area divided by the width – from the water surface elevation measured in feet above sea level. These results are shown in Figures 22-26 in Appendix III. All stations experience some degree of channel incision, particularly since the most intense phase of wing-dam construction and dam closures in the 1950s and 60s. This incision is most dramatic at Kansas City, where the average bed elevation has declined approximately 10 ft, and it is least at Waverly, with at most 1-2 feet of bed decline, and at Hermann, with about 2-4 ft of decline. Hermann and Waverly are the two stations where loss of cross-sectional area appear to be driving flood stage increases, suggesting that channel constriction is the geometrical mechanism driving the observed increases in flood stages.

<u>Stage Indexing</u>

Results of stage indexing for the five Lower Missouri River stations are shown in Figures 27 to 31 of Appendix IV. Recall that indexed frequency curves attempt to <u>incorporate</u> the effects of shifts in the stage-discharge relationship on a river reach into calculations of flood recurrence and flood probabilities. Figures 27-31 show both the unindexed flood frequencies based on recorded stages (in blue) as well as the indexed flood frequencies (in red). In general, the raw stage frequencies agree reasonably well with published flood frequencies based on discharge records for the Lower Missouri River. For example, the frequency of the 1993 flood is estimated in the neighborhood of about 100 years at all five stations analyzed, comparable to the widely circulated discharge-based estimates. At all five stations, the estimated heights of large floods, including events both smaller and larger than 1993, are increased when the data are homogenized to recognize the specific-gage trends. The correction is least dramatic at Kansas City, where the 1993 flood remains the #1 rank event (the largest) even in the indexed data, and the indexed 100 year flood level exceeds the unindexed 100 year flood by (only) 2-3 feet. The correction is most dramatic at Boonville. Prior to indexing, the largest flood by stage at Boonville was the 1993 flood, with a stage of 35.16 ft. Following indexing, the 1993 stage drops to rank #4, behind the 1951, 1943, and 1947 floods. This means that if all the historical flood events had occurred in the present-day conditions of the channel, than those three previous floods would have caused stages higher than observed in 1993. Incorporating this systematic deterioration in the channel at Boonville, stage indexing estimates that the 35.16 ft stage that broke the record in 1993 can be expected to occur every 15-20 years or less in the future.

REFERENCES CITED

Belt, C.B. Jr., 1975. The 1973 flood and man's constriction of the Mississippi River. Science, 189: 681-684.

Biedenharn, D.S., and C.C. Watson, 1997. Stage adjustment in the Lower Mississippi River, USA. Regulated Rivers: Research & Management, 13: 517-536.

Blench, T., 1969. Mobile-Bed Fluviology: A Regime Theory Treatment of Canals and Rivers for Engineers and Hydrologists. The University of Alberta Press: Edmonton.

Branyan, R.L., 1974. Taming the Mighty Missouri: A History of the Kansas City District Corps of Engineers 1907-1971. Kansas City, MO: U.S. Army Corps of Engineers, Kansas City District, 128 pp.

Maher, T.F., 1964. Degradation study of the Middle Mississippi River, vicinity of St. Louis. U.S. Dept. of Agriculture, 970: 424-430.

National Research Council, 1999. Improving American River Flood Frequency Analyses. National Academy Press: Washington.

Pinter, N., R. Thomas, and J.H. Wlosinski, 2001. Flood-Hazard Assessment on Dynamic Rivers. Eos: Transactions of the American Geophysical Union, 82: 333-339.

Pinter, N., R. Thomas, and J.H. Wlosinski, 2000. Regional impacts of levee construction and channelization, Middle Mississippi River, USA. In J. Marsalek, W.E. Watt, E. Zeman, and F. Sieker (eds.), Flood Issues in Contemporary Water Management, p. 351-361. Dordrecht: Kluwer Academic Publishers.

APPENDIX I

SPECIFIC GAGE FIGURES

APPENDIX II

CROSS-SECTIONAL FIGURES

APPENDIX III

CHANNEL INCISION DIAGRAMS

APPENDIX IV

STAGE INDEXING RESULTS