20TH CENTURY STAGE TRENDS ALONG THE MISSISSIPPI RIVER

Thad A. Wasklewicz
Department of Earth Sciences—Geography
E. J. Meeman Biological Field Station
University of Memphis
Memphis, Tennessee 38132

Jack Grubaugh and Scott Franklin
Department of Biology
E. J. Meeman Biological Field Station
University of Memphis
Memphis, Tennessee 38132

Sabine Gruelich
Maître de Conférences
Ingénierie des Milieux Aquatiques et des Corridors Fluviaux (IMACOF)
Université François Rabelais
Faculté des Sciences et Techniques
Parc de Grandmont, bât. B
F-37200 Tours
France

Abstract: River regulation has systematically increased along much of the Mississippi River throughout the 20th century. There is only a cursory understanding of changing hydrological processes along the entire length of the Mississippi River over this same time period. This study compared four measures of river hydrology, at the beginning (1910–1930) and at the end of the 20th century (1980–2000). River-stage data were statistically analyzed from 15 equidistant gauges along the main stem of the Mississippi River. The findings revealed (1) significant changes in components of river hydrology between both time periods and (2) varying patterns of change between the different river segments. The Upper Mississippi River (UMR) experienced significant increases in peak, mean, and minimum monthly stages between the periods, while variance of these same stage conditions declined. The Middle Mississippi River (MMR) exhibited significant increases in the magnitude and variance of river stages. The frequency and duration of flood stages increased between the two periods on the MMR. The Lower Mississippi River (LMR) demonstrated a mixed response during this time period. Gauges at the upper and lower end of the LMR changed similarly to the gauges on the UMR. However, gauges on the central part of the LMR showed decreases in peak, mean, and minimum river stages. [Key words: engineered features, hydrology, Mississippi River, river stage.]

INTRODUCTION

The Mississippi River represents one of the largest regulated rivers in the world. The reasons for river regulation are common to many rivers. Periodic fluctuations in
River stage prompts a need to protect human resources. Often society relies on engineered structures, such as levees and artificial meander cutoffs, to abate flooding. In contrast, low river stages create a need for locks and dams as well as a navigation channel to increase water depths and maintain a year-round transportation network. Numerous engineered structures have been employed along the Mississippi River beginning in the late 19th and early 20th centuries. River regulation intensified during the 1930s with the emplacement of a more systematic array of engineered features. Human modifications to the Mississippi River channel and floodplain have altered the dynamics of the hydrologic processes (Stevens et al., 1975; Knapp, 1994; Smith and Winkley, 1996; Biedenharn et al., 2000; Pinter et al., 2001; Criss and Shock, 2001). For example, Criss and Shock (2001) have identified increases in flood stages of constant discharge along the channelized segments of Middle Mississippi River (MMR) and lower Missouri River, while other nonchannelized segments did not exhibit similar magnitude changes. Pinter et al. (2001) used stage analyses for constant discharges to show large stages increased, while low stages decreased from 19th to the end of the 20th century on the MMR. However, none of these studies have attempted to place the changes in a spatial context along the main stem of the Mississippi River.

Poff et al. (1997) identified five components of hydrologic processes as critical to characterizing the flow regime of rivers and these include: magnitude; frequency; duration; timing, and rate of change of flows. These components set a framework for water quality, energy flux, physical habitat characteristics, and biotic interactions within riverine ecosystems and are essential to their ecological integrity (Karr, 1991). Many studies examining hydrologic processes in rivers have analyzed discharge (De Putter et al., 1998; Baldwin and Lall, 1999; Jones, 2000; Restrepo and Kjerfve, 2000) but few have explored long-term changes in river stage (Gellens, 1991; James, 2000). The lack of research of river stages has resulted from the prevailing view that unlike discharge, stage represents a variable dependent upon other hydrologic parameters (Pinter et al., 2001). However, floodplain biotic communities are directly affected by changes in the seasonal patterns of river stages (Rood and Mahoney, 1999). Furthermore, changes to the magnitude, frequency, duration, or timing of river stages can have a direct impact on the dynamism of riverine environmental conditions and the biological processes of the associated flora and fauna.

Studies investigating changes to surface hydrology on the Mississippi River have tended to focus on particular river segments (Winkley, 1977; Knapp, 1994; Smith and Winkley, 1996; Biedenharn et al. 2000; Pinter et al., 2001) or a single hydrologic parameter (Knapp, 1994, Winkley, 1994; Biedenharn and Thorne, 1994; Wlosinski, 1999; Biedenharn et al., 2000). Criss and Shock (2001) provided a slightly different approach by investigating flood stages across several sites over a large portion of the Mississippi River drainage basin. Their work is more in line with prevailing scientific and governmental objectives that promote holistic interpretations of river hydrology at coarser scales than a river segment (NRC, 1999).

There remains a need to understand systemic changes along the Mississippi River main stem in addition to the findings of Criss and Shock (2001). The current research explores the spatial continuity of several components of river surface
hydrology along a major portion of the Mississippi River, from St. Paul (MN), to the confluence with the Red River (in LA). The magnitude, frequency, duration, and timing of river stages are investigated for two time periods: pre- (1910–1930) and post-systematization (1980–2000). Two specific questions are addressed: (1) how have river stages changed at individual gauging sites between the pre- and post-systematization periods; and (2) what spatial variability exists for river-stage changes along the main stem of the Mississippi River during the 20th century?

METHODS

History of Engineering on the Mississippi River

The Mississippi River has experienced a drastic channel metamorphosis over the last 100 yrs. from human-induced changes to geomorphic and biotic characteristics of the channel and the floodplain (Dynesius and Nilsson, 1994; Knapp, 1994; Smith and Winkley, 1996; Barry, 1997; Biedenharn et al., 2000). Engineered structures appeared on the Mississippi River during the late 19th and early 20th centuries. However, many of these projects were not designed within the context of a centralized plan or with a common configuration, and most failed in their original design. A systematized approach to navigation and flood management was initiated in the 1930s (Fig. 1). Most of the locks and dams and the 2.7-m (9-ft.) navigation channel were started in the 1930s and completed by the 1940s. Flood-control structures (levees and floodwalls) were not finished until the late 1970s (Fig. 1). Sediment-control structures (wing dams, riprap, and other bank stabilizing techniques) were also initiated prior to 1940 and have been continuously modified to the present. This equates to a time period from roughly 1930 to 1975 during which a systematic emplacement of
engineered features occurred along the main stem of the Mississippi River. A similar
time sequence of systematic engineering has been identified for many of the major

**Study Area**

The study covers a major portion of the Mississippi River, from St. Paul to the
confluence with the Red River (Fig. 2). This represents 2560 km of channel, which
is roughly 70% of the entire main stem river length. Three segments were investi-
gated: the UMR extends 1180 km from the St. Croix River, Wisconsin, to the
Missouri River, Missouri; the 314 km of the MMR from the Missouri River, Missouri,
to the Ohio River, Kentucky; and the LMR (1018 km) from the Ohio River to Red
River, Louisiana. Not covered by the current study were the deltaic plain and the
headwaters region.

**Hydrologic Data**

The Mississippi River possesses an extensive network of gauges, which have
been recording river stage since the late 1800s. Approximately equidistant (150 km
apart) USACE (United States Army Corps of Engineers) river-stage gauging stations
were selected for analysis along each river segment. This approach produced seven
gauges along the UMR, two gauges for the MMR, and six gauges along the LMR.
Gauges on the UMR are generally situated approximately halfway between two locks and dams. Nine gauges contained a pre-regulation record to at least 1900 (Table 1). However, missing data for time period 1910 to 1930 made the McGregor and Brickeys gauging stations inadequate for analysis between the pre- and post-systematization time periods. All data were acquired from USACE district offices in digital or paper format. They consisted of daily instantaneous stage readings (generally collected at 8 a.m.) from each station. The stage data were used because our efforts to acquire discharge and hydrograph data were unsuccessful. On several occasions we were told by the USACE regional offices that the data simply did not exist for the earlier years of record.

Therefore, the study relies on specific-gauge records to illustrate the varied response along the Upper and Lower Mississippi River system. The use of specific-gauge techniques isolates the effects of engineered structures and excludes the effects of upstream mechanisms (Winkley, 1977; Pinter et al., 2001). Data analyses can be interpreted based upon the local conditions near the gauge location and any additional increase or decrease caused by upstream mechanisms would be superimposed on the local changes. Therefore, results reflect natural and anthropogenic conditions specific to the river segments described earlier.

Table 1. The 15 United States Army Corps of Engineers River Stage-Gauging Stations Used to Analyze the 20th Century Trends along the Mississippi River\(^a\)

<table>
<thead>
<tr>
<th>Site abbreviation</th>
<th>Segment(^b)</th>
<th>Location</th>
<th>River km</th>
<th>Data available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wab</td>
<td>UMR</td>
<td>Wabasha</td>
<td>145</td>
<td>1936–1999</td>
</tr>
<tr>
<td>McG</td>
<td>UMR</td>
<td>McGregor</td>
<td>352</td>
<td>1878–1891, 1900–1932(^c), 1937–1999</td>
</tr>
<tr>
<td>Cam</td>
<td>UMR</td>
<td>Camanche</td>
<td>549</td>
<td>1939–1999</td>
</tr>
<tr>
<td>Kth</td>
<td>UMR</td>
<td>Keithsburg</td>
<td>684</td>
<td>1900–1999</td>
</tr>
<tr>
<td>Grg</td>
<td>UMR</td>
<td>Gregory</td>
<td>805</td>
<td>1931–1999</td>
</tr>
<tr>
<td>Han</td>
<td>UMR</td>
<td>Hannibal</td>
<td>879</td>
<td>1900–1999</td>
</tr>
<tr>
<td>MoL</td>
<td>UMR</td>
<td>Mosier Landing</td>
<td>954</td>
<td>1939–1999</td>
</tr>
<tr>
<td>GdT</td>
<td>MMR</td>
<td>Grand Tower</td>
<td>1,241</td>
<td>1885–1999</td>
</tr>
<tr>
<td>Col</td>
<td>LMR</td>
<td>Columbus</td>
<td>1,450</td>
<td>1881–1999</td>
</tr>
<tr>
<td>Obi</td>
<td>LMR</td>
<td>Mouth of Obion River</td>
<td>1,641</td>
<td>1928–1999</td>
</tr>
<tr>
<td>Stl</td>
<td>LMR</td>
<td>Star Landing</td>
<td>1,820</td>
<td>1930–1990</td>
</tr>
<tr>
<td>Ros</td>
<td>LMR</td>
<td>Rosedale</td>
<td>2,005</td>
<td>1874–1906, 1911–1928, 1932–1999</td>
</tr>
<tr>
<td>Vic</td>
<td>LMR</td>
<td>Vicksburg</td>
<td>2,256</td>
<td>1887–1999</td>
</tr>
<tr>
<td>Ntz</td>
<td>LMR</td>
<td>Natchez</td>
<td>2,377</td>
<td>1887–1999</td>
</tr>
</tbody>
</table>

\(^a\)The length of the record at each gauge is indicated in the data available column. The river km begin at St. Anthony Falls (0 km) and continue downstream.

\(^b\)UMR = Upper Mississippi River; MMR = Middle Mississippi River; LMR = Lower Mississippi River.

\(^c\)Partial records were supplied for these years. Consequently, this gauge was not used to examine long-term changes.
Winkley (1977) used specific gauge techniques for seven gauging stations along the LMR from Columbus, Kentucky, to Red River Landing, Louisiana, at near bank-full conditions for the time period 1860 to 1975. The current study expands the work of Winkley (1977) by examining more recent trends in stage variability and comparing these results to the UMR. We apply corresponding techniques at three of the same gauges and a fourth gauge not previously examined by the work of Winkley (1977) on the LMR. An additional two gauges from the UMR and a single gauge from the MMR are included for the spatial comparison with the LMR. Pinter et al. (2001) have demonstrated the validity of similar specific gauge techniques for the assessment of flood hazards on the MMR. Biedenharn (1983) has also used specific gauge analyses to identify variation in channel morphology and river stage with the emplacement of a dam.

**Justification for Using Stage Data**

Much of the research pertaining to variability of surficial hydrologic processes has relied on the use of stage-discharge relationships. However, there is a growing body of literature assessing the use of stage data as a means to further scientific knowledge of riverine dynamics (see Pinter et al., 2000, 2001, 2002a, 2002b, and citations within). Pinter et al. (2001) showed historical stage data represent an underutilized source of information. Their research provides evidence that stage data can be used as a supplement to and an independent test of discharge-based analyses of flood frequency. The analyses in the current study use stage data because they provide measures over a longer duration of time at many sites along the Mississippi River (Pinter et al., 2002a, 2002b). It is also the case that stage values represent a direct and precise measure of surface hydrology, while discharge estimates are subject to uncertainties of at least +5% to 15% (Sauer and Meyer, 1992). In further support of the use of stage we also present the fact that stage-frequency curves are used by the USACE and FEMA to establish the regulatory floodplain. These curves also provide USACE with estimates of the economic benefits of various flood mitigation alternatives (Goldman et al., 2002).

Despite the aforementioned advantages, several issues remain in any assessment of stage data. Large changes in stage are often a response to variations in discharge, channel hydraulics, or channel morphology. Discharge and stage change directly when the flow is confined within the natural levees, but once flow overtops the banks, stage-discharge relations do not exhibit a one-to-one correlation (Elliot, 1932). It is also the case that stage-discharge relations are impacted by changes in flow with time and variability in the water-surface slope. Several factors can result in hydraulic changes that impact stage and these include variations in roughness elements above, within, and immediately below the gauge reach, such as vegetation, grain friction, and bedforms to name a few. Some of the possible morphologic adjustments include bed incision or deposition, change in control (i.e., changes to the downstream bars or other features that control the stage through the gauge reach), lateral bank or bar construction or erosion, and levee construction or removal.

Water-temperature fluctuations are also of concern to variation in stage measures. However, Pinter et al. (2000, 2002a) provided evidence that variability...
introduced by temperature into long-term hydrologic time series is random and nonsystematic over-time, and therefore, does not significantly affect the specific-gauge trends. Another concern regarding the use of stage as an independent variable is that stage data do not account for variability associated with reservoir regulation and human activities on the hydrologic record within the tributaries and hence lends further support for specific-gauge techniques. Therefore, precipitation and channel morphometric variability are two major factors that could impact our results using the specific-gauge approach. We address these factors based upon previous research in our interpretation of the results.

Statistical Analysis

We compared river stages at the beginning and end of the 20th century in all of the analyses. The period at the beginning of the 20th century was one in which human-made structures were not consistently engineered or maintained along the Mississippi River and is hereafter referred to as the “pre-systematization period.” By the end of the 20th century human-made structures were consistently engineered and maintained along the section of the Mississippi River investigated by the current study, and this period is hereafter called the “post-systematization period.” To document the pre-systematization period we used river stage records from 1910–1930, whereas the post-systematization period comprised river-stage records from 1980–2000.

River stages at individual gauges were compared for both time periods by repeated two-tail ANOVA to test the equality of monthly peak, mean, minimum, and range of river stages at individual gauging stations given the intervention of systematization of engineered features. Therefore, the pre- (1910–1930) and post-systematization (1980–2000) periods were the independent variables (i.e., the time variable in the ANOVA). Monthly peak, mean, low, and the range of river stages represented the dependent variables that were examined for each gauging station. The analysis tested the null hypothesis that there were no differences in means between the pre- and post-systematization periods. Variability in the four factors was expressed as coefficient of variation for comparison among factors.

We analyzed the interaction of the pre- and post-systematization periods (time) with months to examine differences in the seasonality of river stages. This Time*Month interaction was added to the initial repeated ANOVA to assess if natural or anthropogenic factors had created significant shifts in the timing of any of the hydrologic components. Because we hypothesize human alterations were the cause of river stage changes, we predicted the timing of high and low flows would be the same prior to and following systematization. A change in the timing would be indicative of climatic forcing.

Differences in frequency and duration of peak river-stages at individual gauge sites were examined by repeated ANOVA. Flood stages were calculated by relating stage values to the elevation of the bank (natural levee) adjacent to the gauging station derived from topographic maps. The bank elevations do not represent an absolute flood value; rather they provide a fixed value (data standardization element) from which changes in river stage between the two time-periods could be compared in a
meaningful manner. An absolute flood value was not provided because cross-sectional data for the entire record of the gauges were not available. The number of yearly flood stage events (counts of each day the river stage was above a particular bank elevation) and duration of each event were determined at each gauging site. We used a repeated ANOVA to test the null hypothesis that there were no differences in the frequency and duration of flood stages between the pre- and post-systematic periods. The repeated ANOVA was performed in SAS 8.1 (SAS, 2000).

Limitations of Using the Two Time-Periods

There are some limitations to defining 1930 to 1975 as a shift to a systematic engineered river management scheme. The time frame of systematic engineering is to some degree an arbitrary temporal distinction. Nevertheless, it is supported by historical documentation of the work conducted by USACE along the segments of the Mississippi River (Dobney, 1978; Fremling and Claflin, 1984; Clay, 1986; Smith and Winkley, 1996). The authors did recognize engineering had taken place throughout the entire record of the analyzed stage data, but early engineering designs were relatively ineffective. Therefore, changes in the pre- and post-systematic regulation intervals were analyzed to ascertain repeated measures for investigating the spatial and temporal variability of river stage during the 20th century.

RESULTS

Temporal Trends in River Stages at Individual Gauges

The time effect (pre- vs. post-systematization period) was significant at all gauges for peak, mean, and minimum stages as well as for stage range on the upper and middle reaches (Table 2). All river stage parameters increased on the UMR, MMR,

<table>
<thead>
<tr>
<th>Segment</th>
<th>Gauge</th>
<th>Time effect Pr &gt; F</th>
<th>Time*Month effect Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>Keithsburg</td>
<td>&lt;0.05 &lt;0.05 &lt;0.05 &lt;0.05</td>
<td>0.95 0.99 0.93 0.31</td>
</tr>
<tr>
<td></td>
<td>Hannibal</td>
<td>&lt;0.05 &lt;0.05 &lt;0.05 &lt;0.05</td>
<td>0.31 &lt;0.05 &lt;0.05 0.09</td>
</tr>
<tr>
<td>Middle</td>
<td>Grand Tower</td>
<td>&lt;0.05 &lt;0.05 &lt;0.05 &lt;0.05</td>
<td>0.88 0.88 0.78 0.20</td>
</tr>
<tr>
<td>Lower</td>
<td>Columbus</td>
<td>&lt;0.05 &lt;0.05 &lt;0.05 &lt;0.05</td>
<td>0.90 0.81 0.54 0.98</td>
</tr>
<tr>
<td></td>
<td>Rosedale</td>
<td>&lt;0.05 &lt;0.05 &lt;0.05 0.57</td>
<td>0.78 0.63 0.58 0.73</td>
</tr>
<tr>
<td></td>
<td>Vicksburg</td>
<td>&lt;0.05 &lt;0.05 &lt;0.05 0.09</td>
<td>0.67 0.35 0.44 0.79</td>
</tr>
<tr>
<td></td>
<td>Natchez</td>
<td>&lt;0.05 &lt;0.05 &lt;0.05 0.65</td>
<td>0.48 0.31 0.68 0.64</td>
</tr>
</tbody>
</table>

*Time*Month effect tests for differences in the seasonality between the pre- and post-systematization periods. Significant probabilities are indicated in bold.
Fig. 3. Results from the repeated ANOVA, including (A) difference between the pre- and post-systematization coefficient of variation, and (B) difference between the means (meters) of the different hydrologic components of river stage. Each chart portrays peak, mean, minimum, and the range of river stages. All of the repeated ANOVA were significant except for the river stage ranges at Rosedale, Vicksburg, and Natchez.
and a portion of the LMR that included Columbus, the uppermost gauge on the LMR (Fig. 3). The only exception to this trend was the slightly decreased range at Hannibal in the UMR (Fig. 3B). On the LMR, peak, mean and minimum stages decreased at Rosedale and Vicksburg, and increased strongly (more than 6 m) at Natchez. Differences in range were not significant at these three gauges. The variability of peak, mean, and minimum stages, as measured by the coefficient of variation, decreased on the UMR and at Natchez, while they remained stable at Vicksburg and Columbus (LMR), and increased at Grand Tower (MMR) and Rosedale (Fig. 3A). Variability of range decreased at all gauges with exception of Hannibal.

The change in the interaction Time*Month was not significant except for mean and minimum stages at Hannibal (Table 2). As predicted, this indicates that the timing of high and low stage events is similar for the pre- and the post-systematization period at each of the sites along the Mississippi River. The only exception was the Hannibal gauge, which could have resulted from numerous factors. For example, differences in sedimentation rates at Hannibal and Keithsburg might result in the differences in stage responses through time.

Frequency and Duration of Flood Stages

Flood stages on the UMR and MMR occurred three times more often in the post- than in the pre-systematization period of the 20th century (Fig. 4). Two sites on the LMR showed no significant changes in frequencies (Columbus and Rosedale), while there was a significant decrease in flood stage frequency at Vicksburg (seven times less often in the post-systematization period) and a significant, small increase at Natchez (Fig. 4). There were statistically significant increases in the duration of flood stages at Keithsburg and Grand Tower. An overall decline in flood-stage duration was identified along the LMR, but Vicksburg was the only gauging site to show statistically significant evidence to support this finding (Fig. 4).

DISCUSSION

Trends in River Stages along the Mississippi River

The findings show significant changes in the hydrological components of the mainstem Mississippi River during the 20th century. The predominant pattern was an increase in river stages during the post-systematization period at all gauges except Rosedale and Vicksburg on the LMR. Hannibal was the only gauge that did not show a decline in water-level fluctuations (river-stage range). Marked differences in the hydrologic parameters were identified along the river. The UMR (Keithsburg and Hannibal) showed a higher flood frequency and increased flood duration at the end of the century, associated with a decrease in stage variation. Flood frequency and duration were also found to have increased on the MMR and were accompanied by larger variances in river stages. The greatest diversity in the pattern of changes was identified along the LMR. There were increasing stages and ranges of water level fluctuation at Columbus, with no significant modifications of
other hydrologic parameters. Rosedale and Vicksburg had decreasing stages. Significant decreases in flood frequency and flood duration were found for Vicksburg. Natchez showed increased stages and flooding frequency associated with a decrease in stage variability. Modifications in the range of water level fluctuation only occurred on the upper two sections of the studied river section. This pattern changes at the Columbus gauge. Below this point the range in the river stages between the two time-periods vacillated in a much different fashion.

The Role of Channel Modifications in These Analysis Patterns

Each of these changes was observed to coincide with different degrees of systematic river regulation (pre- and post-systematization periods). The study cannot
demonstrate a causal relationship between river modifications and the changing hydrological components, although numerous authors have demonstrated links in more local studies for some of the parameters integrated in the present study. For example, the construction of locks and dams on the UMR aimed to eliminate low flow periods to allow navigation year round. Our results indicated an increase of minimum river stages observed on this river section that would correspond to the goals of river regulation along this river segment. Winkley (1994) also observed that the artificial meander cutoffs on the LMR in the 1930s and 1940s were immediately followed by modified river stages for a same reference discharge of 33,980 m$^3$ s$^{-1}$ (1,200,000 cfs). River stages decreased within and increased downstream of the section containing artificial meander cutoffs. This corresponds to the widely observed pattern that an artificial increase of bed slope is followed by river incision upstream and aggradation downstream of the modified section (Biedenharn et al., 2000). Our findings, in conjunction with Biedenharn et al. (2000), show a continuation of the trends identified by Winkley (1977). It may suggest the river has reached some equilibrium phase in its adjustment to the artificial meander cutoffs. Furthermore, river incision and aggradation likely explain the diversity of hydrological changes on the LMR observed in this study.

Engineered management schemes can and are altering river dynamics, but the study could not rule out possible changes in climate and land-uses of the Mississippi River. There is a connection between changing river stages and climate variability over the last 100 yrs. A study of Holocene flood frequencies and magnitudes on tributaries of the UMR documented small increases in temperature (1° to 2°C) and changes in mean annual precipitation (10–20%) were accompanied by increases in flood magnitude (Knox, 1993). Knox also reported warmer and drier periods were often associated with the extreme flooding events. The evidence from Knox's research suggests river systems in this portion of the Midwestern United States are responding quickly to regional- and local-scale changes in the hydrologic cycle. Given temperature increases (Pollack et al., 1998; Hansen et al., 1999; Jones et al., 1999) and the highest recorded extreme precipitation events (Kunkel et al., 1999) in the last decade, it is possible some of the changes in river stage from the pre- and post-systematization period is exacerbated by or a direct result of climatic variability. However, the current study has provided evidence that suggests there have been no shifts in the seasonality of river stages that would be indicative of climate change over this time period.

This study could not account for changes in land use and land cover (LULC). Settlement along the Mississippi River led to intensive harvesting of forests, the development of large-scale agricultural practices, urbanization, and the draining of wetlands (IFMRC, 1994). The alteration of LULC has increased the rate of sediment delivery in the UMR (Knapp, 1994; Miller and Nudds, 1995; Theiling, 1999). Changes in sediment quantities moving through the channel have a drastic impact on the stage elevation recorded at a river gauge (Biedenharn et al., 2000). Impoundment along the main stem of the river for navigation has increased the retention of sediment and it is likely that sediment stored in pools behind the dams and in the fields of wing dams further enhances the increase of flow magnitude (Grubaugh and Anderson, 1989). Tile drainage is a common practice throughout much of the
Mississippi River drainage basin and its impacts on the components of the surface hydrology of the Mississippi River are likely to be significant.

**Implications to the Management and Restoration of the Mississippi River**

The focus on understanding the hydrologic impacts of the river management and the potential for restoration have been based on studies conducted along the UMR (Junk et al., 1989; IFMRC, 1994; Hey and Phillipi, 1995; Johnson et al., 1995; Sparks, 1995; Woltemade, 1997). The results along the UMR and MMR are uniform because there are consistent causal influences within and adjacent to the channel, specifically locks and dams as well as levees. The locks and dams have a significant control on the low stage conditions, while the levees, wing dams (dikes) and floodwalls change the high stages. The river stages on the LMR are not as uniformly impacted as stages on the UMR and MMR. The LMR has an extensive system of levees, wing dams (dikes), and navigation channels, but the artificial meander cutoffs have been intertwined with these previous engineered structures. Sections of the LMR experience higher degradation or aggradation rates, which can be linked to distinct responses to changes in river stage magnitude. Therefore, restoration and management schemes designed on the UMR may be relevant for the MMR, but might have little application to the LMR. A need remains for holistic management of the Mississippi River drainage basin, but with a hierarchical approach that addresses the spatial discontinuities identified by the current study along the length of the Mississippi River.

**CONCLUSIONS**

The Mississippi River has experienced a drastic change in the scale of its engineered management scheme over the 20th century. The findings from this study provide a broader perspective of the significant spatial variability of the river stages over the century. The establishment of a systematic engineered management scheme coincided with, but was not directly correlated to, changes in stage variability and magnitude. However, the changes were not consistent for the UMR, MMR, and LMR segments. The findings indicated the peak, mean, and minimum river stages along the UMR and MMR significantly increased from the pre- to the post-systematization time-period. The LMR peak, mean, and minimum stages decreased along river reaches that had artificial meander cutoffs and increased along sections not impacted by the human induced cutoffs. There were declines in the variance of river stage range (peak–min stage) on the UMR, which indicated although river stage magnitude increased; monthly fluctuations in water levels had declined throughout the 20th century. The MMR experienced an increase variance in range over the last 100 yrs., while the LMR did not show a statistically significant difference in the variance of river-stage range.

There was an overall trend toward increases in flood-stage frequencies along the main stem of the Mississippi River. However, the UMR and MMR were the only two segments with statistically significant increases in flood-stage frequencies. There were significant increases in the duration of flood stages on the UMR (Keithsburg)
and MMR (Grand Tower), but declines on the LMR. Vicksburg was the only gauge on the LMR to have a statistically significant decrease in duration. The timing of monthly river stages was also investigated and it was determined that there were no significant changes in the timing of peak, mean, low-flow events over the last century.

The data derived from the hydrologic parameters and results have direct implications to the management and restoration of the Mississippi River ecosystem. The baseline data supply managers with an understanding of the spatial variability in river stage responses over the last century. The data provide information with regard to the amount of change in the stage magnitude, frequency, and duration. There is a clear indication from this study that river stage does not respond in the same way along the entire length of the Mississippi River. Sound decision-making on changes in one section of the river must be met with a proper understanding of the ramifications of these alterations to sites upstream and downstream of these locations. A simple “one-size-fits-all” approach will not address the spatial variability of this large river system. Management or restoration projects should account for the strong intervariability of hydrologic conditions along the main stem of the Mississippi River.

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