SPECIFIC GAGE ANALYSES OF STAGE TRENDS ON THE MIDDLE MISSISSIPPI RIVER

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Abstract. A specific gage record is a graph of stage for a specific discharge at a particular gaging location plotted against time. A specific gage graph can suggest trends in increasing or decreasing stage for specific discharge, but does not directly provide cause-and-effect relationships for observed trends.

This study utilizes a specific gage record developed at the St. Louis gage on the Middle Mississippi River to identify any increasing or decreasing trends in river stage, and to determine if these trends can be attributed to the construction of navigation dikes. The period of record utilized in this study was the post-USGS period (1933 at St Louis). This time period provides a long term, consistent record of the modern-day river system, and represents a period of considerable dike construction. The historical measurements prior to the early 1930s were not included in the specific gage analysis because there is too much uncertainty associated with comparisons of discharge measurements made with varying methods. The uncertainty of the pre-USGS discharge measurements has been referenced by numerous internal and published sources.

For the 1930s to 2009 period at St Louis, there was a slight decreasing trend in stages at the lower flows (100,000 cfs and 200,000 cfs), but no significant increasing or decreasing trends at the higher flows.

In summary, based on the specific gage record, there has been no significant increase in stages for the within-bank flows that can be attributable to dike construction. Any increases in overbank flood stages may be the result of levees, floodplain encroachments, and extreme hydrologic events and cannot be attributed to dikes based solely on the specific gage records. The precise cause and effect relationships among the various features along the Middle Mississippi River are extremely complex and difficult to quantify using only specific gage records.

BACKGROUND

The Middle Mississippi River (MMR) extends from the mouth of the Ohio River (RM 0) near Cairo, IL to the mouth of the Missouri River at RM 195. The U.S. Army Corps of Engineers (USACE) is the primary Federal agency responsible for design, construction and management of navigation and flood control projects along many of the major rivers of the nation, including the MMR. Numerous river engineering structures have been implemented on the Middle Mississippi River to improve the channel for navigation and flood control. These include river training structures such as dikes (both pile dikes and stone dikes), bendway weirs and chevron structures, and bank stabilization structures. In addition to these in-channel structures, the overbank areas have been significantly impacted by levees and floodplain development since about the early 1900s. Concerns about the effects of in-channel and overbank structures on flood stages have been raised by several authors. The objectives of this study were to utilize specific gage records for the St. Louis discharge gaging station on the Middle Mississippi River to identify any increasing or decreasing trends in the data, and to determine if these trends can be attributed to the construction of navigation features such as dikes, bendway weirs and chevrons.

APPLICATION AND LIMITATIONS OF SPECIFIC GAGE RECORDS

According to Blench (1966):

There is no single sufficient test whether a channel is in-regime. However, for rivers, the most powerful single test is to plot curves of "specific gage" against time; if the curves neither rise nor fall consistently the channel is in-regime in the vicinity of the gaging site for most practical purposes.

A specific gage record is a graph of stage for a specific discharge at a particular gaging location plotted against time. A channel is considered to be in equilibrium if the specific gage record shows no consistent increasing or decreasing trends over time. A key factor is that sufficient, reliable data must exist at each time period for which data is plotted on the graph. For example, if no stage and discharge measurement data are made during a period no information is available from that period. Transferring information from a prior measurement or rating curve is inappropriate.

There are two methods for developing a specific gage record: the rating curve method and the direct step method. For the rating curve method, the first step is to establish the stage-discharge relationship at the gage for each year for the period of record being analyzed. The stage-discharge relationship is generally depicted in the form of a stage-discharge rating curve, which is a plot of the measured water discharge versus the observed stage at the time of measurement, usually an annual rating curve. A regression curve is then fit to the data and plotted. The regression curve is sometimes fit by eye, but the use of a curve fitting technique is recommended to provide a more consistent procedure that minimizes subjectivity. Since the specific gage record reflects only observed data it is important that the regression line does not extend beyond the limits of the measured data for that year of observation. For example, if the maximum discharge measured in a particular year was 450,000 cfs, then there would be no specific gage point for flows greater than 450,000 cfs for that year. For this reason there may be some years in which the gage reading for very large or small discharges may have to be omitted. In this case, there will be a gap in the specific gage record for that year. It is also important to use only the actual measured discharge values in the development of the specific gage record. It is often tempting to use the computed daily discharge values to increase the number of data points and improve the statistics of the rating curve. While this may result in more available data points, these values are not valid and risk masking actual trends. Once the rating curve for each year has been developed, the stage for a specific discharge can be determined and that value is plotted versus the year on the specific gage plot.

For the direct step method, the data comes directly from the discharge measurements and not from a rating curve. Each specific discharge is represented by a flow range usually in the range of 5% to 10%. For example, if a 5% range is used, a flow of 200,000 cfs would be represented by all measured discharges between 190,000 cfs and 210,000 cfs. The stage values within this range of discharges are then plotted against the associated dates of measurements to produce a specific gage record. As opposed to the rating curve method where there is only a single value each year, the direct step method may produce several points depending on the number of measurements in that year. The variation between measurements is then evident in the specific gage plot, not an annualized average as with the rating curve method.

The development of a specific gage record is a relatively straightforward procedure; however, the interpretation of specific gage records is more complex. One of the most common mistakes in the utilization of specific gage records is to place too much emphasis on a short time period. The specific gage records on most rivers exhibit considerable variation about a mean value. There may even be cyclic patterns in the record. Therefore, localized trends in the specific gage record over relatively short time periods may not reflect a true progression of the river. Another common mistake is to identify a single long-term trend over a long time period that may actually exhibit two or more distinct trends. This is illustrated in Figure 1 that shows the specific gage record for the Mississippi River at Arkansas City for the period 1880 to 2004. According to the long term trend line over the 1880 to 2004 period, the Arkansas City gage would be classified as being in a degradational regime. However, this would clearly be an oversimplification of the trends at Arkansas City. The degradational period was limited to a short period of time between about the mid 1930s and early 1950s. As shown in Figure 1, the river would more appropriately be classified as being in dynamic equilibrium since the 1950s. The obvious mistake is to assume a long-term single trend, and not to accept the data that is suggesting that some dramatic event occurred during the period 1938 to 1948. That dramatic event was the abrupt shortening of the Mississippi River during the Cutoff Period. While the specific gage does not suggest the cause of the dramatic change, the river engineer must investigate potential cause-and-effect relationships.

Specific gage records are an excellent tool for assessing the historical stability at a specific location. However, specific gage records have limitations that must be recognized. First, a specific gage record only indicates the conditions at a particular gaging station and does not necessarily reflect river response upstream or downstream of the gage. Second, a specific gage record does not provide any indication about future degradation or aggradation trends. Extrapolation of specific gage records into the future is extremely risky and is generally not recommended. Interpretation of specific gage records can be subjective. For this reason, it is recommended that the visual observations of trends be tempered with statistical analyses. The variability and uncertainty of the data must be recognized. For example, with the rating curve method, each year is represented by a single data point of stage for the given discharge, which may mask the uncertainty of the data. The rating curve from which this single data point was derived may have had five feet or more of variability in it. Therefore, even though the specific gage record is a valuable tool used by river engineers, it is recommended that it be coupled with other assessment techniques and models to assess cause-and-effect relationships that may be manifested as trends in the specific gage.

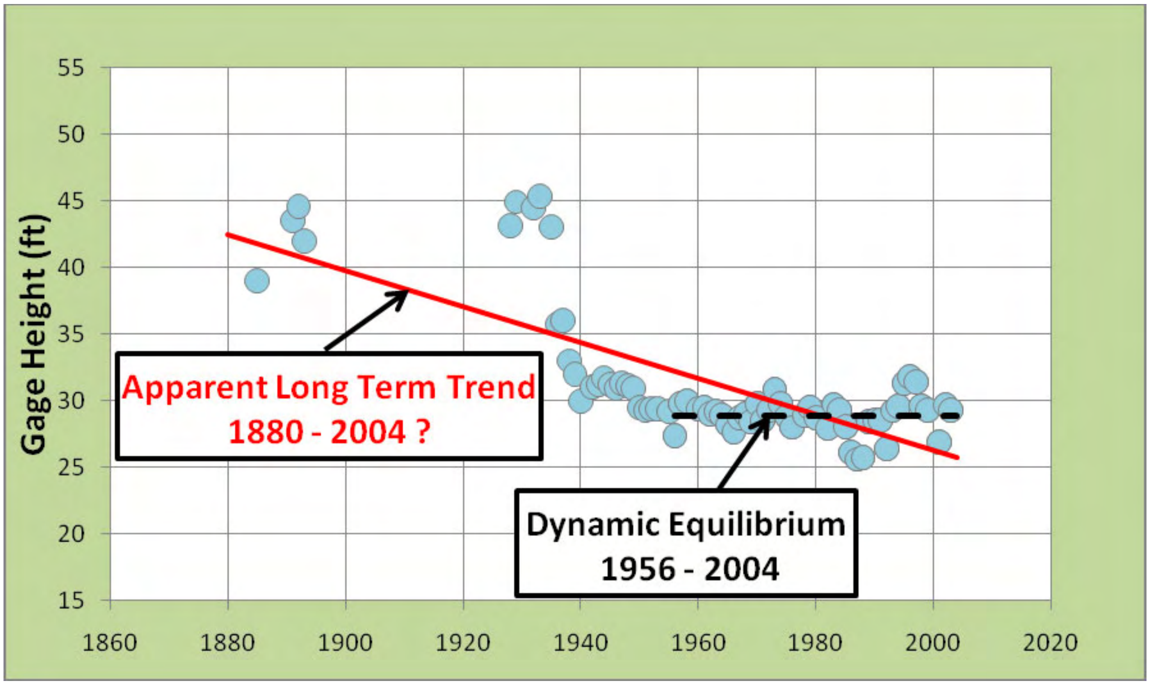

Figure 1. The specific gage record for the Mississippi River at Arkansas City for the period 1880 to 2004 for a flow of 1,000,000 cfs.

STATISTICAL ANALYSIS

While a specific gage graphs can be inspected visually to identify any increasing or decreasing trends in the data, a statistical analysis of the data should be conducted to determine the statistical significance of any trends. Two statistical parameters (R^2 and p-values) are used to assess the data. The R^2 value provides a measure of the amount of variability in Y (stage) that is explained by X (time), and erroneously suggests that a cause-and-effect relationship exists between time and stage. For example, an R^2 of 0.8 implies that 80% of the variability in stage can be explained by time. Conversely, an R^2 of 0.2 implies that only 20% of the variability in stage can be explained by time. The p-value assesses the statistical significance of an apparent trend. The following p-Value criteria were utilized for this study. If the p-Value is less than 0.01, then the null hypothesis is rejected and the slope of the trend line is classified as being significantly different than zero: a trend does exist. If the p-Value is greater than 0.1, then the null hypothesis is accepted and the slope of the trend line is not significantly different than zero: there is no significant trend in the series. If the p-Value falls within the range of 0.01 to 0.1, then the results are inconclusive. Overall trends should reflect an integration of both the visual inspection and the statistical analysis.

An analysis finding a relatively high R^2 value and a p-value less than 0.01 may give the river engineer confidence that a specific gage trend exists, but does not establish a cause-and-effect relationship. Samaranayake (2009) recommends five criteria that are essential for reaching statistically valid conclusions about cause and effect. These are:

1. Establish that the data to be used in drawing conclusions are specific to the hypothesis of interest, are of good quality, and collected in a manner that does not give rise to a biased or wrong conclusion.
2. Use valid statistical methods that are appropriate for the problem at hand.
3. Establish that the results obtained by the analysis are statistically significant.
4. Establish a cause and effect relationship before one attributes statistically significant associations to a particular cause.
5. Quantify what fraction of the observed effect is attributable to the cause.

LITERATURE REVIEW

The use of dikes to narrow and deepen a river for navigation purposes is well-established in the literature. Peterson (1986) defines dikes as training structures that extend out from the bank into the flow, and she suggests five purposes for which dikes may be used:

- Cut off side channels and chutes
- Concentrate a braided river into a single channel
- Constrict a channel to increase depth
- Realign a river reach, and
- Prevent bank erosion and protect structures along the bank and bridge and utility crossings.

Jansen (1979) presents design criteria for groynes (dikes) and present relationships developed by de Vries (1974) to estimate the amount of channel degradation that will occur as a consequence of dike design alternatives. Vries (1974) proposed using a direct relationship between the ratio of width constriction and the ratio of depth increase to estimate improvements in navigation depth for the Magdalena River. Training dikes are a navigation tool used to improve the local sediment transport capacity of the main channel, thereby minimizing the need for maintenance dredging. Fenwick (1969) stated that dike construction resulted in a more efficient section and maintained greater channel depth. Dikes are designed to constrict the low and intermediate flows, creating a deeper and more efficient channel. These references strongly suggest a cause-and-effect relationship between dike construction and channel incision.

Biedenharn et al (2000) conducted a detailed study of the sedimentation trends of 28 individual dike fields on the Lower Mississippi River that suggests the largest impacts of the dikes occur in the initial response period (first 10 to 15 years following dike construction) after which the response decreases significantly. Biedenharn et al (2000) also found that the dikes either produced a larger, more efficient channel, or had no significant impact on the overall channel cross section at all.

The morphology of the Middle Mississippi River is a result of numerous natural factors such as floods, droughts and tectonic activity and anthropogenic factors such as dams, levees, dikes, and revetments. Sorting out the cause and effect of these individual factors is difficult. Over the years there has been considerable attention paid to the effects of levees and dikes on flood stages. Maher (1964) and Kazman (1972) attribute rise in stages along the river to levees which prevent the floodwaters from spreading out over the floodplain. Belt (1975) and Stevens et al. (1975) stated that a combination of navigation works and levees have caused significant rise in flood stages, but the question of the relative effects of dikes and levees on high-water stages in the

Middle Mississippi River can be answered only by a careful engineering study of the records available for this river.

Flow measurements prior to about 1932, when the responsibility for gaging shifted from USACE to the USGS, were made using techniques and equipment that are not comparable to later measurements; therefore, comparison of 19th and 20th century stages and discharges, or study of this data set to determine relative effects of dike and levees are of questionable value.

The Stevens et al. (1975) paper triggered a series of discussion papers by Dyhouse (1976), Stevens (1975), Strauser and Long (1976) and Westphal and Munger (1976) challenging the results of the Stevens et al. (1975) study. Dyhouse (1976) suggested that Stevens et al (1975) had used data from an atypical Mississippi River reach to draw conclusions about the entire Middle Mississippi River. Stevens (1976), Strauser and Long (1976), and Westphal and Munger (1976) pointed out that flow measurements prior to about 1932 were inconsistent with respect to method and may have over-estimated the early flows by as much as 30%.

Westphal (1976) stated, *"Clearly, the channel constriction brought about by installation of an individual dike has to have at least a temporary local effect on stage-discharge relations. However, the variety of stage responses with respect to time which exist at selected stations in the study area suggest that the effect of dikes may be locally restricted and/or that long-term and short-term stage responses to dike installations may be different in magnitude and direction."*

Reinecke (1935) reports that measurement began at the St. Louis gage in 1866, and the maximum observed (measured) discharge prior to 1935 was 870.000 cfs on April 24, 1927 at a stage of 35.6 feet. The estimated (not measured) high discharges of 1,300,000 cfs on June 27, 1844 at a stage of 41.3 feet and 1,040,000 cfs on June 10, 1903 at a stage of 38 feet were also reported by Reinecke (1935).

Reinecke (1935) states that all stream flow observations by USACE were taken from small boats or barges, and most of the data acquired by the USGS were taken from bridges. Prior to the USGS sampling period, the data were collected at many different locations, and with various sampling devices. Prior to 1928, the vast majority of the measurements were made using floats and rods, and meters were only used about 13% of the time. Meters became the dominant method between 1928 and 1932, but floats and rods were still in use. Even though both the USGS and USACE were using Price meters, the meters and associated equipment of the USACE were obsolete in comparison to the USGS method and equipment.

The historical data were obtained from Reinecke (1935) and a series of data reports in the U.S. Army Corps of Engineers, Mississippi River Commission office indicated that very few discharge measurements at the higher flows were made during this period. For example, for flows greater than 650,000 cfs, there were no measurements until 1909 when 10 flows were measured. The two flows of about 1,000,000 cfs in 1892 were identified as being approximate and therefore, should not be considered valid. After 1909, only a few intermittent high flows were measured until 1927 when 16 measurements were made. The limited number of measurements at the higher flows during this period is problematic in developing reliable specific gage records.

Pinter et al. (2001) have developed a specific gage for the Mississippi River at St. Louis for the period 1860s to about 2000. Pinter et al. (2001) presented data to suggest that rising flood stages are the result of levees, constructed by USACE for flood control, and navigation dikes, constructed by USACE to maintain an authorized navigation channel. His primary evidence for a continuing trend of increasing stage for a selected discharge was a specific gage graph with an apparent trend for 700,000 cfs that rises about 3 meters from 1860 to 2000. Most of that rise occurs within the approximate period of 1930 to 1942, during the transition between USACE and USGS measurement techniques and equipment. Similar rises, at discharges of 400,000 cfs and 500,000 cfs, also are shown. The pre-USGS portion of the record prior to 1932 used by Pinter et al. (2001) includes data that is questionable. Comparison of simultaneous measurements confirms that the pre-USGS measurements over-estimated the actual discharge. The recorded stage should be associated with a lower discharge for this period. Because of the questionable data we have excluded the pre-USGS data in the specific gage analysis discussed later in this paper.

A specific gage record was developed for the St Louis gages (Figure 2). Three time periods were analyzed: (1) Pre-1973; (2) 1973 – 2009; and (3) the entire time period. The starting dates for the St Louis gage is 1933. While analyzing the specific gage record, it was decided to break the record into pre- and post 1973 periods. This was done because it was observed that some of the stage trends were not continuous throughout the entire period of record and often exhibited a shift in the early 1970s. The 1973 break point was selected for several reasons. First, 1973 corresponds to a major flood that had followed a low flow period for the previous fifteen to twenty years. According to Dyhouse (2009), the 1952 to 1972 period was "*remarkably flood free. The peak flood level at St. Louis during this period was only 35.9 ft in 1969, or 5.9 ft. above flood stage*". The St Louis gage record was remarkably constant throughout the entire period. The pre- and post 1973 periods are also considerably different with respect to the amount of dike construction. The pre-1973 period was one of intense dike construction with 14,615 feet of dikes constructed in the St Louis reach. In the post 1973 period the length of dikes constructed in this reach was only 7,001 feet. The historical data prior to the USGS taking over the measurements was not included in the analysis. The specific gage records were first inspected visually to identify any increasing or decreasing trends in the data, and a statistical analysis was developed.

ST. LOUIS SPECIFIC GAGE ANALYSIS

The specific gage record developed for the St Louis gage without pre-USGS data for the period 1933 to 2009 is shown in Figure 2. Table 1 provides a summary of the stage trends analysis. The flows used in the specific gage record range from 100,000 cfs, to 700,000 cfs. The bankfull condition at St Louis occurs at a gage height of about 30 feet on the gage (Figure 2). As indicated, all flows at or below 400,000 cfs are contained within top bank. The 500,000 cfs flow occurs near the bankfull stage, and the 700,000 cfs flow is well above the top bank elevation. Also shown is a plot of the cumulative dike length constructed in the 20 mile reach of river between RM 180 and RM 160. A slight decreasing trend in stage was identified for the 100,000 cfs and 200,000 cfs flows during the period 1933 to 2009. However, for the flow range from 300,000 cfs to 500,000 there were no trends in stage observed. At 700,000 cfs, a visual inspection of the data might suggest a very slight increasing stage trend. However, there is considerable variability in the data (R^2 = 0.12) and the apparent trend is not statistically significant. It is also important to recognize that the elevated stages during the 1993 flood strongly influence the visual perception of an overall increasing trend. However, as shown in Figure 2, the stages in the post-1993 period had returned to about the same levels as prior to 1993.

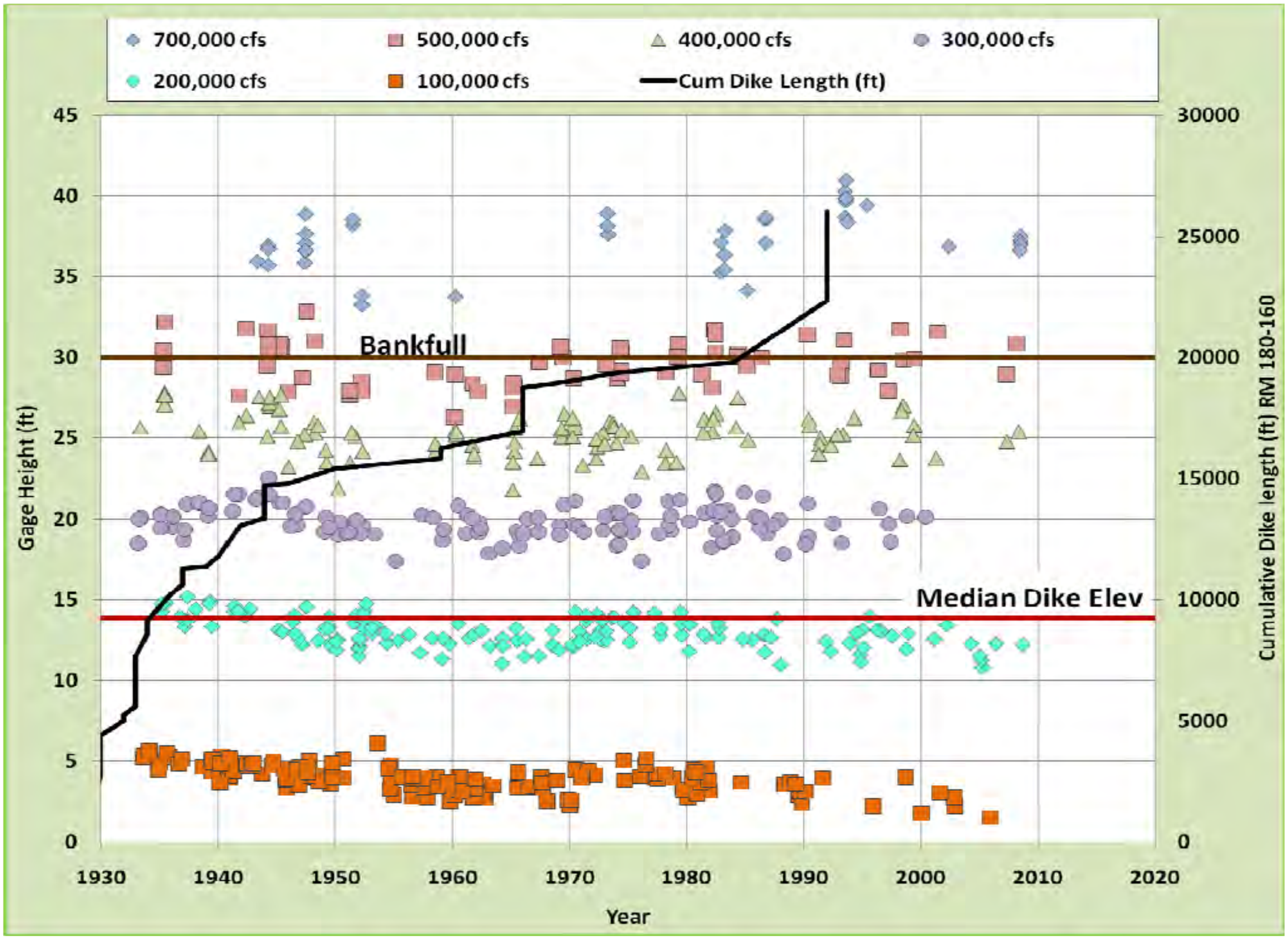

Figure 2. Specific gage record for the St Louis gage for the period 1933 to 2009 and analysis table.

Table 1. Summary of stage trend analysis at St Louis

Period	Flow (1000 cfs)	Statistical Trend*	R^2	Overall Trend **	Cumulative Dike Length (ft) ***
1933 - 2009	100	(-) S	0.351	SDT	21,616
	200	(-) S	0.190	SDT	
	300	(-) NS	0.019	NT	
	400	(-) NS	0.059	NT	
	500	(+) NS	0.003	NT	
	700	(+) SI	0.124	NT	
1933 - 1973	100	(-) S	0.430	SDT	14,615
	200	(-) S	0.240	SDT	
	300	(-) S	0.110	NT	
	400	(-) S	0.210	NT	
	500	(-) S	0.200	NT	
	700	(-) NS	0.170	NT	
1973 - 2009	100	(-) S	0.510	SDT	7,001
	200	(-) S	0.260	SDT	
	300	(+)NS	0.000	NT	
	400	(+) NS	0.000	NT	
	500	(+) NS	0.014	NT	
	700	(+) NS	0.001	NT	

Legend

***** Trend indicated by statistical (p-Value) analysis. A P-Value criterion is given in Section3.4. ***(-)*** and ***(+)*** indicate a decreasing or increasing slope of the regression line. ***S*** – Statistically Significant, ***NS*** – Not Statistically Significant, ***SI*** – Statistically Inconclusive

******Overall Trend is based on statistical analysis and visual observation of data. ***DT*** – Decreasing Stage Trend, **IT** – Increasing Stage Trend, ***NT*** – No Stage Trend, ***SDT*** – Slight Decreasing Stage Trend, ***SIT*** – Slight Increasing Stage Trend

******* Cumulative dike length constructed during time period for a distance of approximately 20 miles downstream of the gage. 1930 was the starting date for the cumulative dike length for all three stations.

It has been proposed that river engineering structures have caused an increase in stages, particularly at flood stage. This argument is based primarily on the interpretation of specific gage records. In this section, the dike construction history in each reach is correlated with the specific gage records to determine if there are any relationships that can be identified. The dominant navigation structures over the past century have been dikes. Chevrons and bendway weirs are relatively new river training structures that have only been in use since the 1990s. For this reason, the focus of this discussion is on effects of the dikes. Levees are another dominant feature along the Middle Mississippi River. A detailed chronology of levee constriction on the

Middle Mississippi River is provided by Dyhouse (2009). Levee construction and floodplain development has been significant.

The specific gage record at St. Louis tracks the changes in stage over time. The identification of the causal mechanisms responsible for any observed changes is complex since there are so many interrelated factors that can impact the morphologic trends. In an effort to determine if the dike construction program has affected stages, the cumulative constructed dike lengths can be compared to the observed trends of the specific gage records.

Examination of Figure 2 and Table 1 shows that between 1930 and 1972, there were 14,615 feet of dikes built. In the post-1973 period there were 7,001 feet of dikes built. The only response identified in the specific gage record that can be attributed to the dike construction is a slight decreasing trend in the low flows (100,000 and 200,000 cfs). For the moderate flows (300,000 cfs - 500,000 cfs), where the hydraulic impacts of the dikes should be the greatest, there were no stage trends observed. The only flow, in which an increasing trend was investigated, although not statistically significant, was at 700,000 cfs, which is well above the top bank elevation, and would be more affected by the levees and floodplain encroachments than the dikes. In summary, there has been over 4 miles of dikes constructed in this reach during the 1933 to 2009 time period, with no increases in stage trends at or below top bank. Since there were no stage increases below top bank, it is difficult to provide an adequate engineering explanation for how the dikes could be causing an increase in stages above the bankfull condition.

CONCLUSIONS

An analysis of the specific gage records at St. Louis was conducted to identify morphologic trends, and determine if these trends could be attributed to river engineering structures constructed in the system. The following are the major conclusions from this study.

- The historical measurements from 1866 to 1932 at St Louis were not included in the specific gage analysis for the following reasons:
    1) There is too much uncertainty associated with making comparisons of discharge measurements made with varying methods. Comparison of simultaneous measurements confirms that the pre-USGS measurements over-estimated the actual discharge.
    2) The post-USGS period (1933 at St Louis) provides an adequate long term consistent record of the modern-day river system, and represents a period of considerable dike construction.
- Typically, the top elevation of the dikes is between about 10 and 16 feet below top bank.
- For the 1930s to 2009 period at St Louis, there was a slight decreasing trend in stages at the lower flows (100,000 cfs and 200,000 cfs), but no significant increasing or decreasing trends at the higher flows.
- Prior to 1973 (a time period covering about 40 years at St Louis), there were 2.8 miles, miles of dikes constructed within a 20 mile reach downstream of the St. Louis gage. During this time there were no increasing stage trends observed at any flows at the gage. A slight decreasing trend was observed at the lower flows at St Louis. In the post-1973 period, the length of dikes constructed in the St Louis reach was 1.3 miles. During this

period, a slight decreasing trend was observed at the lower flows at the St Louis gage. No increasing stage trends were observed for within bank flows at any of the gages.

In summary, based on the specific gage records, there has been no significant increase in stages for the within-bank flows that can be attributable to dike construction. Any increases in overbank flood stages may be the result of levees, floodplain encroachments, and extreme hydrologic events; and cannot be attributed to dikes based solely on the specific gage records. The precise cause and effect relationships among the various features along the Middle Mississippi River are extremely complex and difficult to quantify using only specific gage records.

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