Specific Gage Analyses of Stage Trends on the Middle Mississippi River

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Abstract

This study utilizes specific gage records developed at the three long term discharge gaging stations on the Middle Mississippi River (St. Louis, Chester and Thebes) 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 and early 1940s at Chester and Thebes). 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 for the following reasons:

- There is too much uncertainty associated with making comparisons of discharge measurements made with varying methods.
- The inconsistency with respect to the location of the discharge ranges during this period introduces another level of uncertainty.
- There is insufficient measured data at the higher flow ranges to produce reliable specific gage records.

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. At Chester for the period 1942 to 2009, there was a slight decreasing trend at 100,000 cfs, a slight increasing trend at 300,000 cfs, and no significant trends at 200,000 cfs or 400,000 cfs. Increasing stage trends were observed at both 500,000 cfs and 700,000 cfs. At Thebes for the period 1941 to 2009, there were no significant trends at 200,000 cfs and 300,000 cfs, while slight increasing trends were observed at 400,000 cfs and 500,000 cfs. An increasing trend was observed at 700,000 cfs.

Upon closer examination of the specific gage trends, it was observed that the apparent long term trends were not continuous, but rather a shift in stages occurred in the early 1970s. For this reason, stage trends identified for the entire period from 1930s to 2009 can be misleading. Breaking the record into Pre-and Post 1973 periods may provide a more realistic understanding of the system. Prior to 1973 (a time period covering about 40 years at St Louis and 30 years at Chester and Thebes), there were 2.8 miles, 5.1 miles, and 8.8 miles of dikes constructed within a 20 mile reach downstream of the St. Louis, Chester and Thebes gages, respectively. During this time there were no increasing stage trends observed at any flows at the three gages. 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, Chester, and Thebes reaches was 1.3 miles, 1.5 miles, and 0.8 miles, respectively. 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. At Chester, increasing stage trends were observed for the overbank flows of 500,000 cfs and 700,000 cfs.

In summary, based on the specific gage records, there have been no significant increase in stages for the within-bank flows that can be attributable to dike construction. Any increases in overbank flood stages are most likely 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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1.0 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. A review of the existing literature associated with stage changes on the Middle Mississippi River was conducted, and an assessment of the application and limitations of specific gage records is also provided.

2.0 Objectives of Study

The objectives of this study were to utilize specific gage records developed at the three long term discharge gaging stations on the Middle Mississippi River (St. Louis, Chester and Thebes) 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.

3.0 Application and Limitations of Specific Gage Records

Perhaps one of the most useful tools available to the river engineer or geomorphologist for assessing the historical stability of a river system is the specific gage record. 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 data are made during a period no information is available from that period; transferring information from a prior measurement or rating curve would be inappropriate.

3.1 Analysis Procedures

There are two methods for developing a specific gage record. One may be referred to as the rating curve method and the other as a 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 flows 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.

3.2 Analysis Interpretation

The development of a specific gage record is a relatively simple, 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 long-term 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 3.1, which 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 3.1, 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.

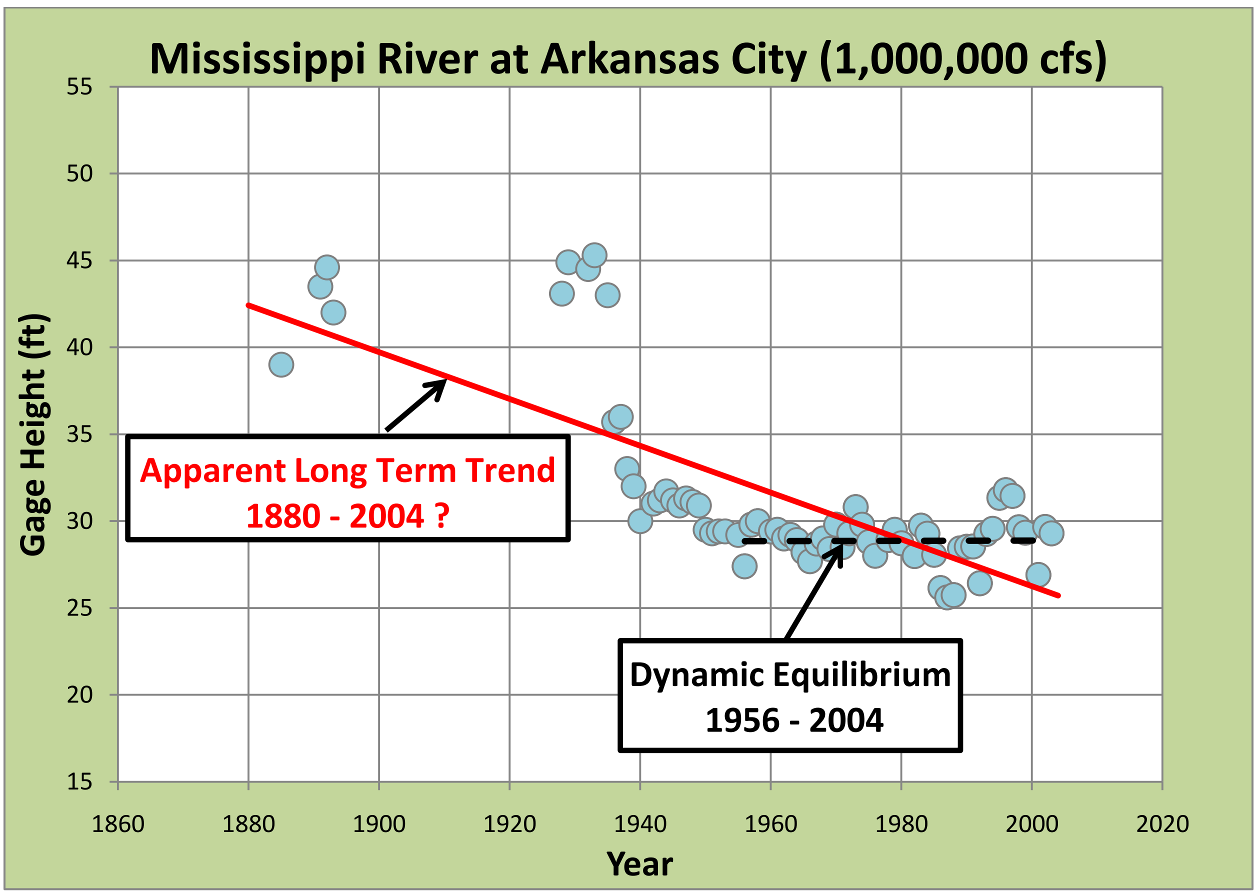

Figure 3.1 The specific gage record for the Mississippi River at Arkansas City for the period 1880 to 2004 for a flow of 1,000,000 cfs.

3.3 Analysis Limitations

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 an open mind that utilizes other assessment techniques and models to assess reach conditions, or to make predictions about the ultimate response on a river.

3.4 Statistical Analysis

Specific gage graphs can be inspected visually to identify any increasing or decreasing trends in the data. However, a statistical analysis of the data should be conducted to determine if any trends are statistically significant. 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). 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 are recommended. 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. It should be recognized that the statistical results are not absolute and therefore, should be tempered with the visual assessments and experience. Consequently, the 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. It should be stressed that the independent variable in a specific gage record is time which simply reflects an integration of all the various factors such as cutoffs, levees, dikes, floodplain encroachments, hydrologic events, dams, etc, that may be affecting the stage. 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*.

4.0 Previous Studies

This section is divided into two sub-sections: published Literature Review, and Historical Discharge Measurements. Much of the information in the Historical Discharge Measurements section comes from unpublished memoranda and agency reports.

4.1 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) present 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. This approach was used as the design method for that project.

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. Dikes are designed to constrict the low and intermediate flows, creating a deeper and more efficient channel. On the Middle Mississippi River, dikes are of two principle types, permeable and impermeable. The response of the channel to the construction of dikes is site specific and depends upon a number of factors such as dike type (permeable or impermeable), dike elevation, configuration (level crest, sloping crest, stepped up or stepped down), dike angle and length, sediment characteristics (size and load) of the channel, and the hydraulic and hydrologic characteristics of the channel. However, there are some general trends associated with dikes that typically occur. First it should be recognized that the hydraulic effects of dikes will vary with stage. The top elevation of a dike is often designed well below the top bank elevation to minimize impacts of dike construction at higher flows. Secondly, it must be recognized that the hydraulic and sedimentation impacts of dikes also change with time. When first constructed, the cross sectional area of the channel will be reduced due to the presence of the dikes. However with time, the dikes will typically induce sediment deposition in the area between the dikes, and increase the area and depth in the main channel due to erosion. In his report on the State of Knowledge of Channel Stabilization in Major Alluvial Rivers, Fenwick (1969) noted:

> *The accumulation of sediment and the retardation produced by the dike system cause the main channel section to carry a larger proportion of the water than it did in the absence of the dike system, thereby increasing the current and the sediment transport capacity. As a result, a more efficient section and greater depth are maintained in the main channel section.*

Biedenharn et al (2000) conducted a detailed study of the sedimentation trends of 28 individual dike fields on the Lower Mississippi River. For this study, the channel was divided into three distinct areas (main channel, pools, and sandbars) based on the classification scheme developed by Cobb and Magoun (1985). The pools are basically the area between the dikes as defined by the area circumscribed by the bank line and a line connecting the channel-ward tips of the dikes. The sandbar areas were defined as the bar area between the pool boundary and the -10 foot Low Water Reference Plane (LWRP) contour. The boundary of the main channel is the remainder of the channel up to the -10 foot LWRP contour. Although there was considerable uncertainty and variability in the individual dike field trends, some general trends were observed. According to their report:

- *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.*
- *The pool (area between the dikes) response is dominated by decreases in surface area, volume, and depth.*
- *The main channel response was dominated by increases in surface area, volume, and depth. The most significant enlargement of the main channel occurs during the initial period immediately following dike construction.*
- *The sandbar area (identified as a transition area between the main channel and the pools) was highly variable, experiencing both scour and fill.*
- *The volume trends for the overall reaches (combined main channel, pools, and sandbars) indicate that the overall reaches have either enlarged or experienced no significant change, while the surface area showed no significant change or minor decreases. Thus, it appears that the dikes have 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) stated that a combination of navigation works and levees have caused significant rise in flood stages.

Stevens et al. (1975) reported on the impact of dikes and levees on river morphology and flood stages, stating that the levee system was a major factor in negating flood damages on the Middle Mississippi River for the 1973 flood. Stevens et al (1975) state that the dike fields were built to attain and maintain the 9-ft, low flow navigation channel, and that the Middle Mississippi River has been deepened for navigation by decreasing channel width with rock and pile dikes. Steven et al. (1975) also lists the top 10 flood discharges and stages of the Mississippi River at St. Louis prior to 1975. From these data, they then compare the reported 19th century flood stages with 20th century flood stages for equal discharges, and suggest that all discharges greater than 300,000 cfs the flood stages in the 20th century are greater. In their conclusions is stated, *"Although flood stages are now higher than those under natural conditions, levees prevent flood damage when the Middle Mississippi River exceeds bankfull stage. Under natural conditions flood damages occurred whenever the river exceeded bankfull stage." Stevens et al (1975) concluded that "The question of the relative effects of dikes and levee 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."*

As will be discussed in the next section, flow measurements prior to about 1932 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. Stevens et al (1975) attributed apparent increases in stage at St Louis during the 1973 flood to rock and pile dikes and to levees. 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) conducted a study to determine if the aggregate effect of dike construction over a reach would be a reduction in channel width and a stage increase for flows in that reach. Westphal 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."*

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 the graph presented as Figure 4.1, which is a specific gage graph. Using the apparent trend lines shown, a flood stage indexing procedure was then developed with the purpose of enabling the prediction of future flood heights and related parameters. Jemberie et al. (2008) "refined" the specific gage approach by creating 49 specific gage relationships for locations without measured discharge data from 18 actual stage and discharge sites.

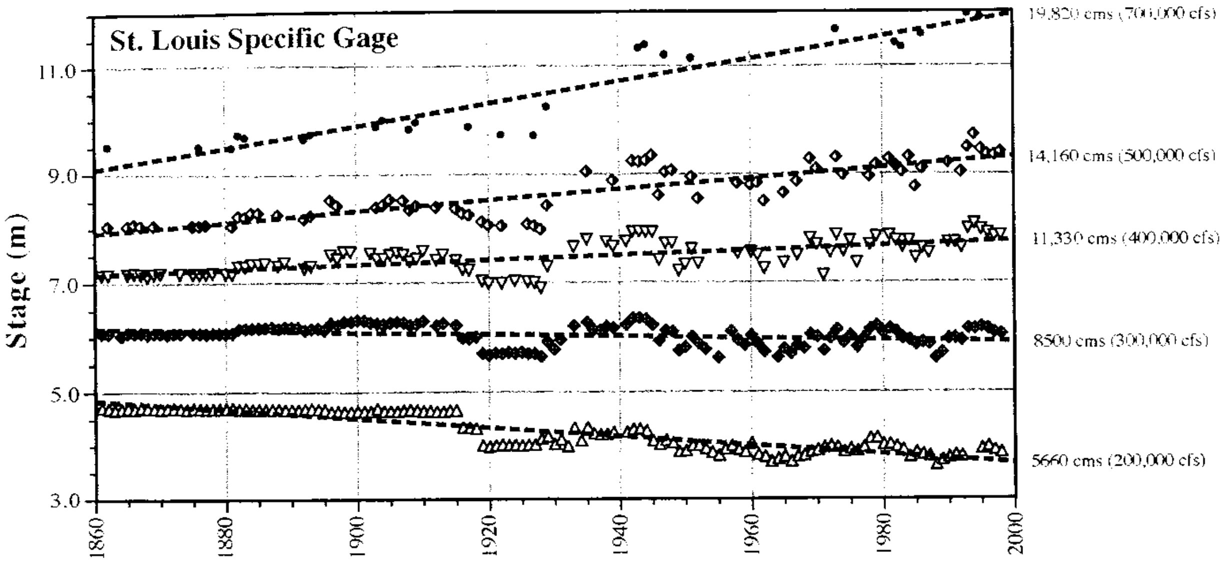

Figure 4.1 The specific gage graph was suggested by Pinter et al. (2001) to show apparent trends in stage through time.

Of interest in reviewing Figure 4.1 (from Pinter et al 2001), is the relatively abrupt increase in stage for flow between the approximate period of 1930 to 1942. For example, the apparent trend line for 700,000 cfs rises from about 9.5 meters in 1860 to approximately 12 meters in 2000, and most of that rise occurs within the abrupt rise occurring in the approximate period of 1930 to 1942. Similar rises, at discharges of 400,000 cfs and 500,000 cfs, also are shown. These relatively rapid changes in stage did not escape earlier river engineers. As discussed in the next section the Corps of Engineers initiated a number of studies beginning in the mid 1930s to determine the causes of these apparent stage increases.

4.2 Historical Discharge Measurements

Historical measurement data begins in 1866. 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. Not only were different types of measuring devices utilized, the method and procedures differed. Also, there were only a limited number of measurements at the higher flows during this period, which is problematic in developing reliable specific gage records.

Figures 4.2 and 4.3 summarize the measurement methods used, the number of measurements, and the magnitude of the discharges measured at St Louis. These 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 entitled, "Results of Discharge Observations, Mississippi River and its Tributaries and Outlets". As indicated in Figure 4.2, 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. Not only were the measurements being made by different instruments, methods and techniques, the location of the discharge range also varied through time. The discharge measurements were made at 18 different locations between 1866 and 1932. Figure 4.3 shows the number of measurements made within four discharge ranges at St Louis. The data indicates 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. Similar data are presented in Figures 4.4 through 4.7 for Chester and Thebes. Examination of these figures reveals similar problems associated with varying measurement methods and locations, and limited data at the higher flows. At Thebes, there were a number of measurements at the higher flows (> 650,000 cfs) in the early 1900s. However, there is the additional problem that the recorded stage readings are at Cape Girardeau or Gray's Point. The Thebes gage is also subject to backwater effects from the Ohio River which adds another level of uncertainty into the analysis of stage trends.

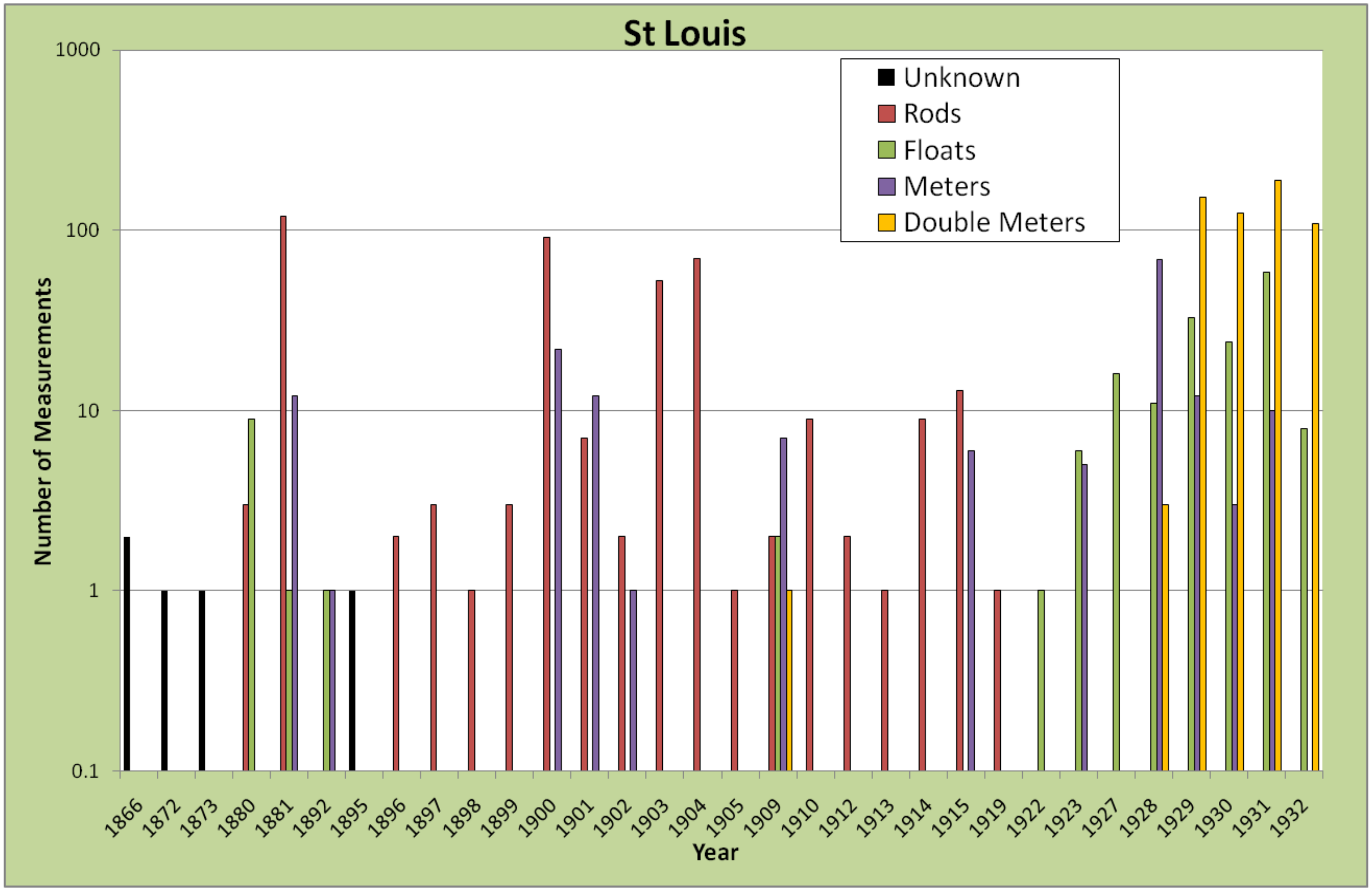

Figure 4.2 The number of measurements made with various devices at St Louis from 1866 to 1932.

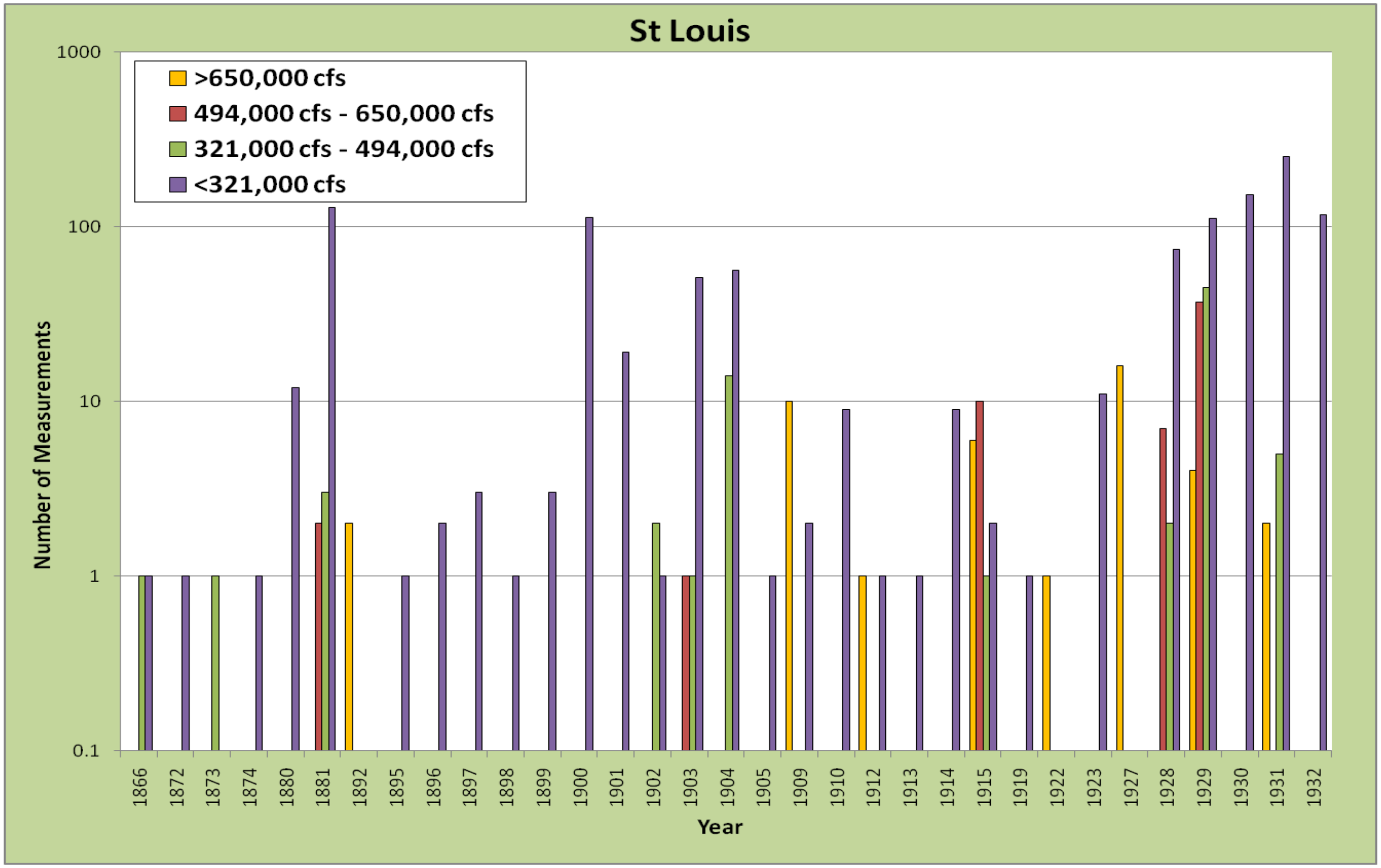

Figure 4.3 The number of measurements made in four discharge ranges at St Louis from 1866 to 1932.

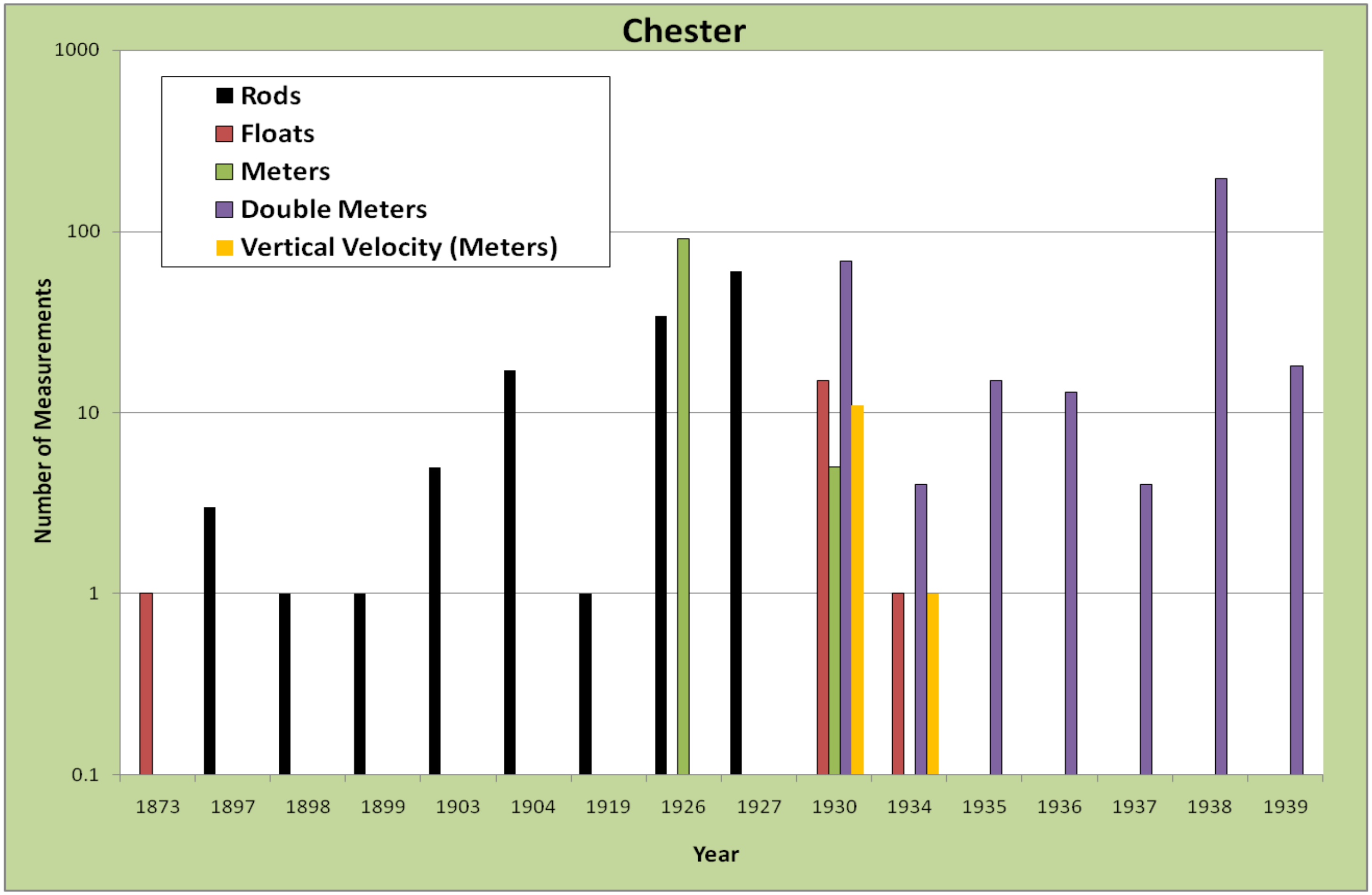

Figure 4.4 The number of measurements made with various devices at Chester from 1873 to 1939.

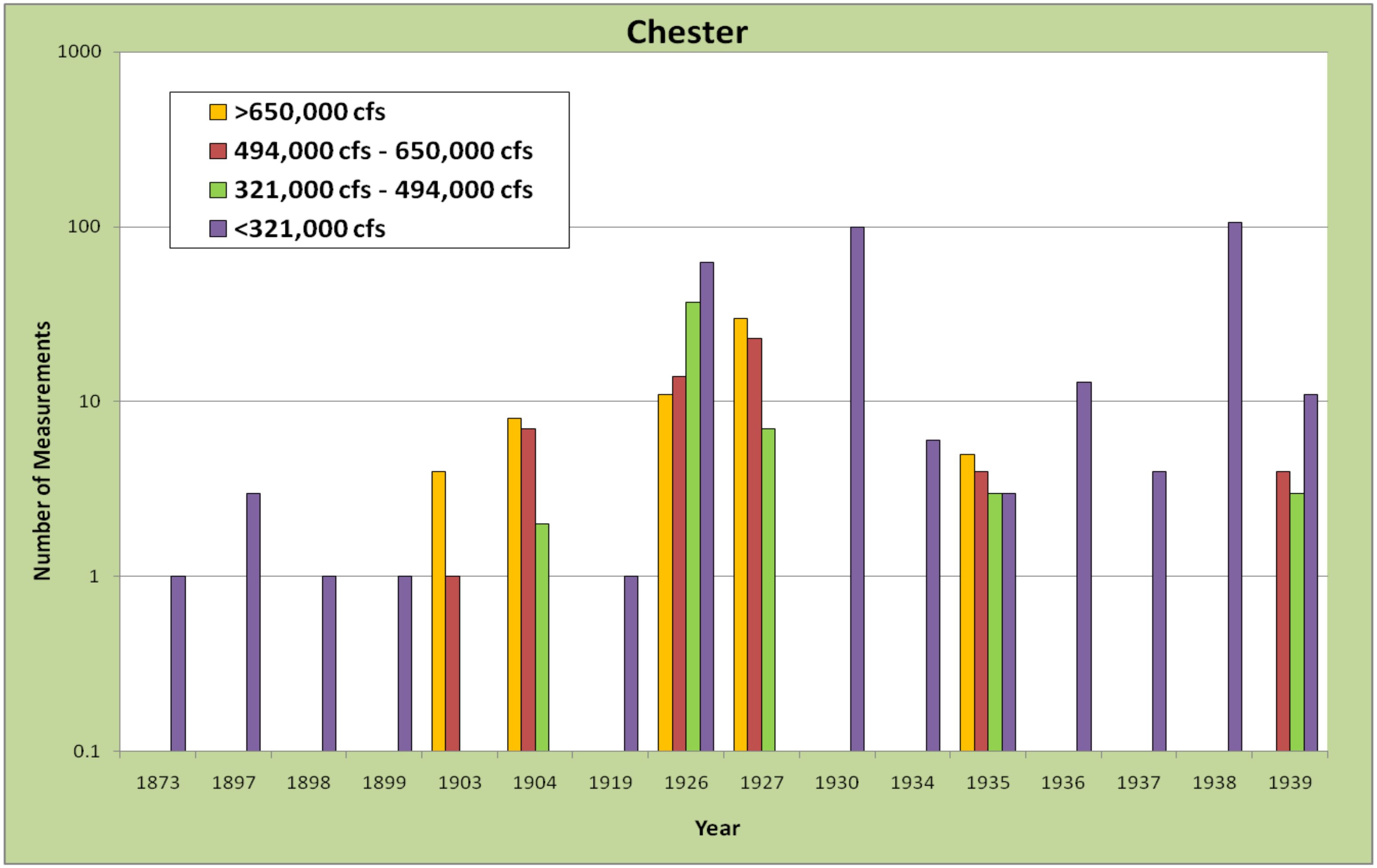

Figure 4.5 The number of measurements made in four discharge ranges at Chester from 1873 to 1939.

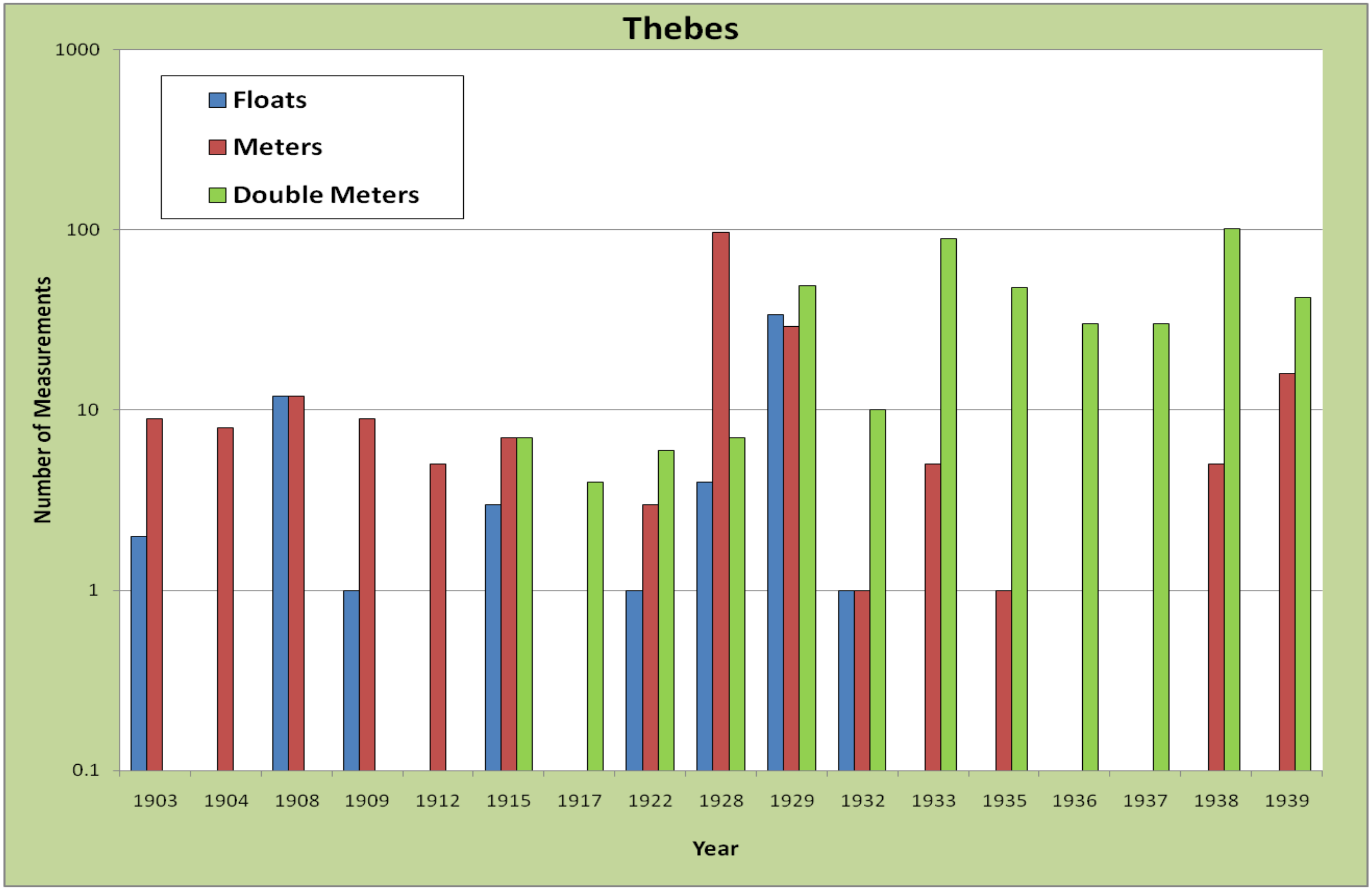

Figure 4.6 The number of measurements made with various devices at Thebes from 1903 to 1939.

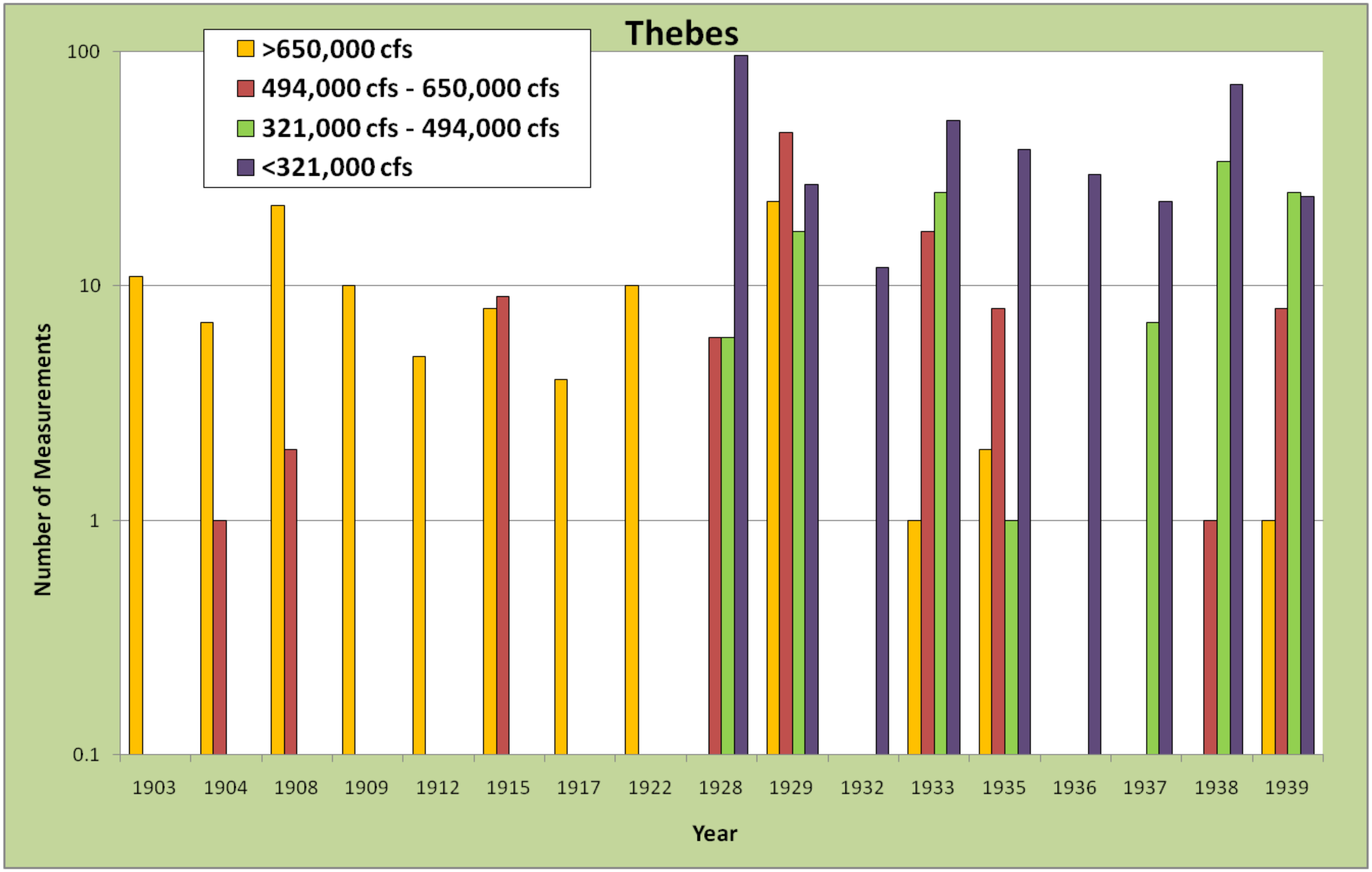

Figure 4.7 The number of measurements made in four discharge ranges at Thebes from 1903 to 1939.

The most recent transmittal letter associated with a series of data and memorandum reporting on the investigation of comparative discharge measurements is from Col. R. E. Ressegieu, District Engineer to the Division Engineer, Upper Mississippi Valley Division. The date of the letter is 26 May 1952. The earliest of the attached material is in 1935 and continues to the 1952 date. The following information was taken from the 1952 file.

A memorandum from Lowell C. Oheim, Surveyman to The Area Engineer, Second Field Area, St. Louis, Missouri, dated 29 August 1935, page 2, paragraphs (d), (e), and page 3, paragraph (i) provides details of the two methods used:

- *"The equipment of the United States Geological Survey was of a light portable type, designed to offer the least resistance to the current, when submerged, Bullet-shaped meter weight, with a plane surface on the bottom weighing from fifty to three hundred pounds, were used alternately. Horizontal and vertical fins fastened to the back end of the weights held them parallel to the flow, and in a horizontal plane at all times. The meter staff was made of polished, stainless steel, 1/8-inch and ¾-inch wide, and was suspended so as to offer least resistance to the flow. The current meter was of a small design, adapted to the thin staff, yet similar in working parts to the large Price Meter (now used by the United States Engineer Department). Electric contacts points in the meter head were arranged to register either each revolution or each fifth revolution of the meter turbine. The reel used to raise and lower the meter apparatus was also of small design; it was equipped with a counter to register depths, and was easily operated by one man. The cable used on the reel was 1/10-inch in diameter and had an electric conductor core that served as the primary line of a telephone circuit to the meter.*
- *The party operated by the United States Engineer Department was rigged with the standard equipment, which consisted of three Large Price Meters, a ¾-inch round brass meter staff, a seventy-five pound meter weight, a length of 3/8-inch steel supporting cable, and a length of two-circuit electric cable ½-inch in diameter. "*
- *On June 3, 1935, vertical curve observations were made by the United States Engineer Department. During the observations, difficulty was encountered in lowering the meter beyond a depth of twenty-five feet, with only seventy-five pounds of weight attached. More meter weights were attached until a total weight of two hundred pounds was tried. While anchored in forty-six feet of water it was found that in order to rest the meter within one foot of the river bottom, it was necessary to play out fifty-nine feet of the supporting cable. At this depth the angle of drift of the weights and meters was measured at forty degrees. Since the cable described a curve under water instead of a straight line, it was impossible at the time to arrive at a true correction to be applied to the line. The objective then was the design of equipment that would reduce the angle of drift of the weights and meters."*

The previous paragraphs document the difficulty using the USACE equipment and techniques to measure Mississippi River discharges. 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 conclusion of a memorandum to the Division Engineer, UMVD, St. Louis, Missouri prepared on 16 March 1945, page 19, and paragraph 38 is as follows:

> *"In view of the fact that the physical reduction in floodway capacity, after flood control projects were established and regulating works constructed, was practically negligible and in view of the fact that the USGS used modern and improved equipment to measure stream flow and that there would be a natural tendency towards improvement of method with the acquisition of experience it is believed that the USGS discharge measurement more nearly represent the actual amount of stream flow. Therefore, the reduction in floodway capacity was not an actual physical reduction but an apparent reduction caused by the discrepancy in the accuracy of measuring stream flow by older methods and equipment."*

Dieckmann and Dyhouse (1998) report that the USGS began discharge measurements at the St. Louis bridge using the Price current meter after 1931. The Price current meter had been patented 25 August 1885, No.325, 011. The original Price meter apparently was much larger than the present Price A meter, and one of the changes that occurred as the USGS began discharge measurements was the advent of the smaller, modern meter. However, the combination of improvement to the meter and the cable suspension system and the move from small boats and barges to a fixed bridge location made a significance difference in measurement accuracy. Dieckmann and Dyhouse (1998) report on a series of joint tests performed simultaneously between the USGS, using the Price meter suspended from a bridge and the USACE, using double floats and old style meters suspended from floating equipment. They report the difference between the USGS measurements and USACE double floats to be 10% at discharges of 400,000 cfs to 500,000 cfs to over 15% at discharge of 700,000 cfs. In comparing the USACE old style meters with the USGS, the USACE readings were 4% higher at 530,000 cfs to 15% higher at 670,000 cfs. In both comparisons, the earlier measurements would have recorded a greater discharge than the later equipment, and the greater the true discharge the greater the error. This could have a significant impact on the shape of the specific gage record since, by definition, the specific gage record should compare stages for the same discharge. For example, if the pre-USGS measurements are 10% greater than the USGS measurements then the stages in the earlier period would be consistently lower than the stages in the later period since they would actually reflect stages at a lower discharge. The following graph (Figure 4.8) was prepared from data recorded in June and July 1935, entitled "Comparison of Discharge Measurements at St. Louis, Mo – 1935".

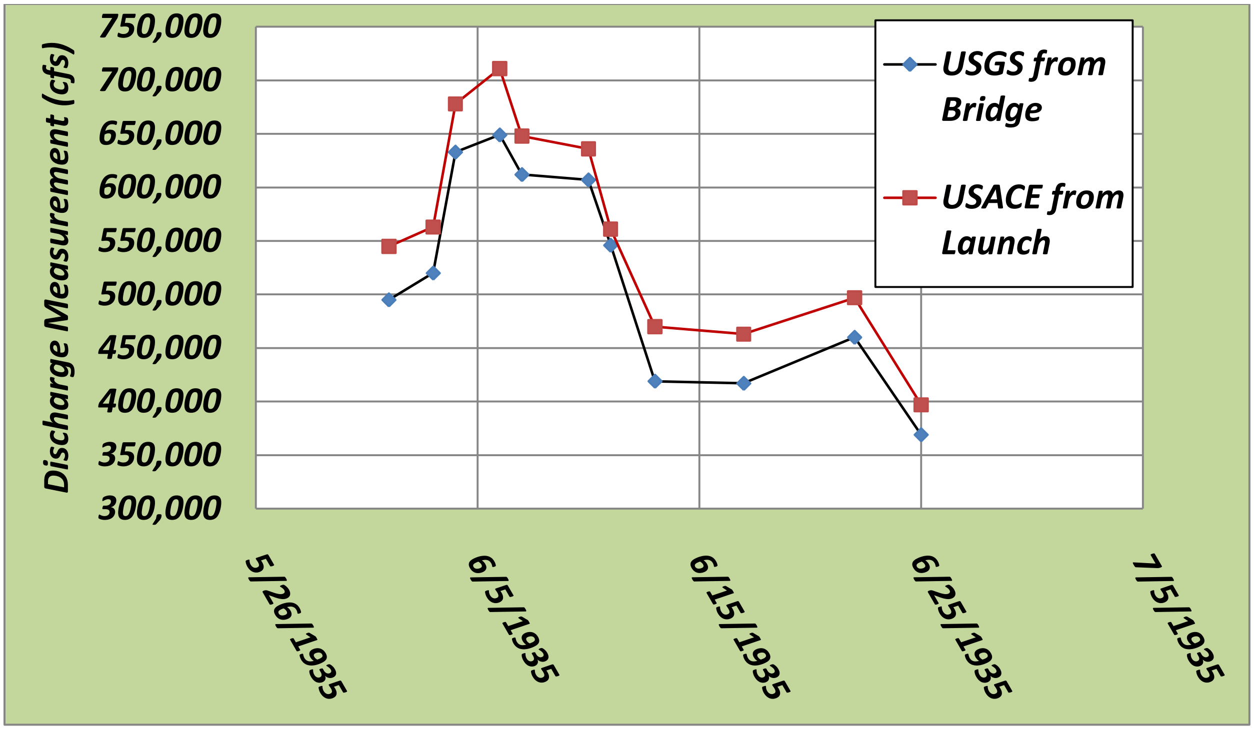

Figure 4.8 The graph displays the data collected in 1935 during simultaneous measurements using USGS and USACE meters. Note that the USACE equipment consistently over-estimated the USGS measurement.

The following table was taken from the 15 March 1945 memorandum, pages 15 and 16, paragraph 33. A rating curve was developed from plotting results of discharge measurements taken by the USGS during the period June 1933 – June 1935 from the Municipal Bridge at St. Louis. The USACE points were taken from a rating curve from measurements made approximately 2.7 mile downstream from the Municipal Bridge during the period August 1934 – July 1935. The increasing difference between the two sets of data as the stage increases is significant.

Table 4.1 Discharges from Rating Curves

Elevation (ft)	USGS Discharges (ft)	USACE Discharges (ft)	Difference (%)
406	415,000	424,000	2
408	465,000	474,000	2
410	518,000	540,000	4
412	578,000	620,000	7
414	642,000	716,000	12
416	710,000	832,000	17
419	840,000	1,060,000	26

In summary, as the stream gauging responsibilities on the Middle Mississippi River shifted from the USACE to the USGS, different methods and more modern equipment significantly affected stage and discharge relationships. Pinter et al. (2001) have developed a specific gage for the Mississippi River at St. Louis for the period 1860s to about 2000. The pre-USGS portion of the record prior to 1932 used by Pinter et al. (2001) includes data that is questionable. 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 in the following section. The rationale for this decision is:

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 inconsistency with respect to the location of the discharge range introduces another level of uncertainty.
3. There is insufficient measured data at the higher flow ranges to produce reliable specific gage records. It would be an inappropriate use of the available data to use a rating curve that was developed for a different time period.
4. The post-USACE period (1933 at St Louis and early 1940s at Chester and Thebes) provides a long term, consistent record of the modern-day river system, and this period includes a significant period of dike construction.

5.0 Middle Mississippi Specific Gage Investigations

Specific gage records were developed for the St Louis, Chester, and Thebes gages (Figure 5.1, 5.2, and 5.3, respectively). Three time periods were analyzed: (1) Pre-1973; (2) 1973 – 2009; and (3) the entire time period. The starting dates for the St Louis, Chester and Thebes gages were 1933, 1942, and 1941, respectively. While analyzing the specific gage records, it was decided to break the records 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*". It was observed that there was a sharp increase in stages in 1973, particularly at the higher, overbank flows. These increases were most pronounced at Chester and Thebes; 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, 27,183 feet, and 46,535 feet of dikes constructed in the St Louis, Chester and Thebes reaches, respectively (Table 5.1). In the post 1973 period the length of dikes constructed in these three reaches were only 7,001 feet, 7,721 feet, and 4,200 feet, respectively. The historical data (pre-1930s at St Louis and pre-1940s at Chester and Thebes) prior to the USGS taking over the measurements was not included in the analysis. The rationale for the exclusion of these data is presented in Section 4.2.

The specific gage records were first inspected visually to identify any increasing or decreasing trends in the data. Next, a statistical analysis of the data was also conducted to determine if any trends are statistically significant. The results of the interpretation of the specific gage records are shown in Table 5.1. The overall trends that are identified in Table 5.1 reflect an integration of both the visual inspection and the statistical analysis. The cumulative length of dikes constructed in each reach was also determined in an effort to establish any relationships between dike construction and stage trends.

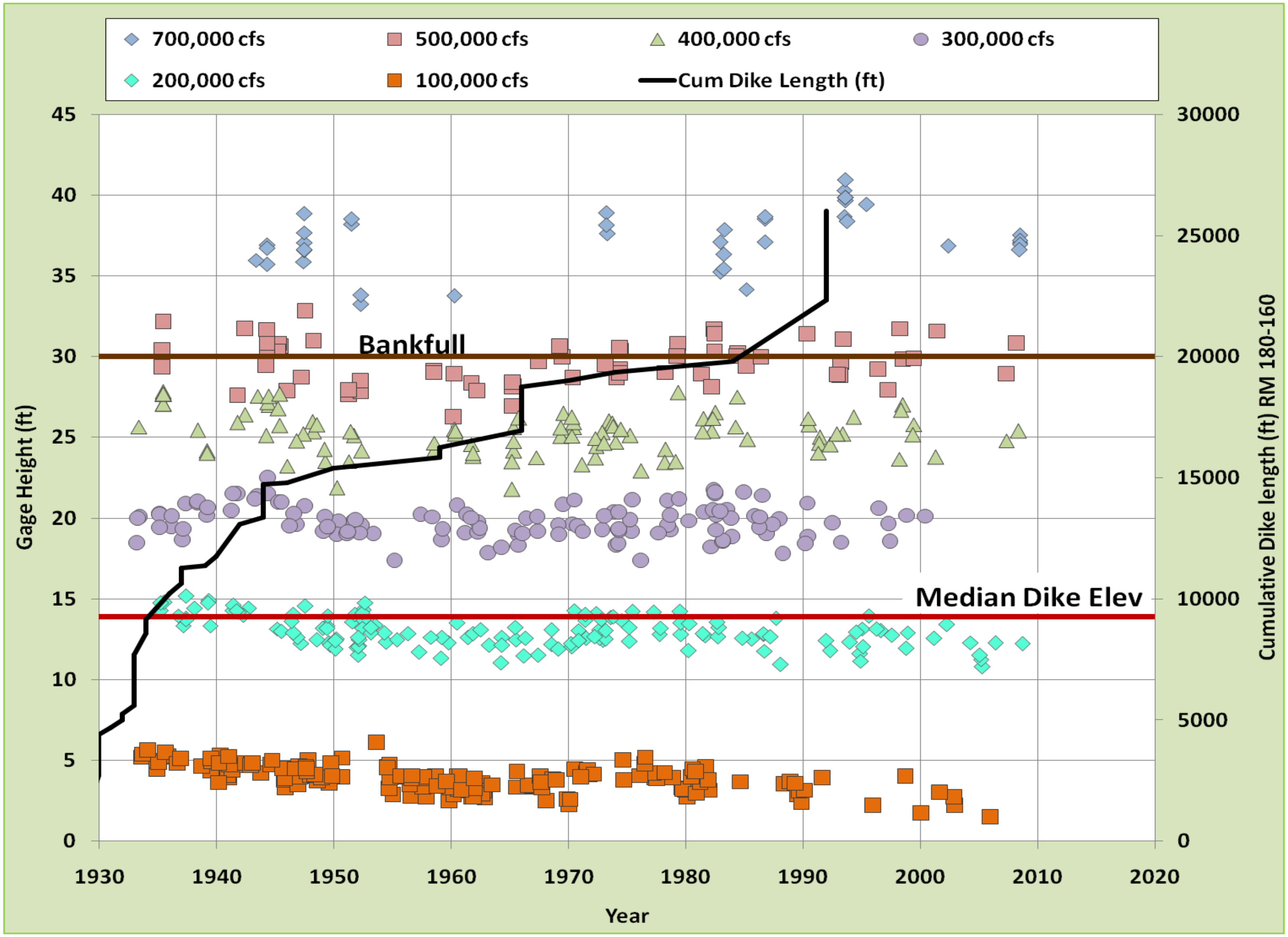

Figure **5.1 Specific gage record for the St Louis gage for the period 1933 to 2009**

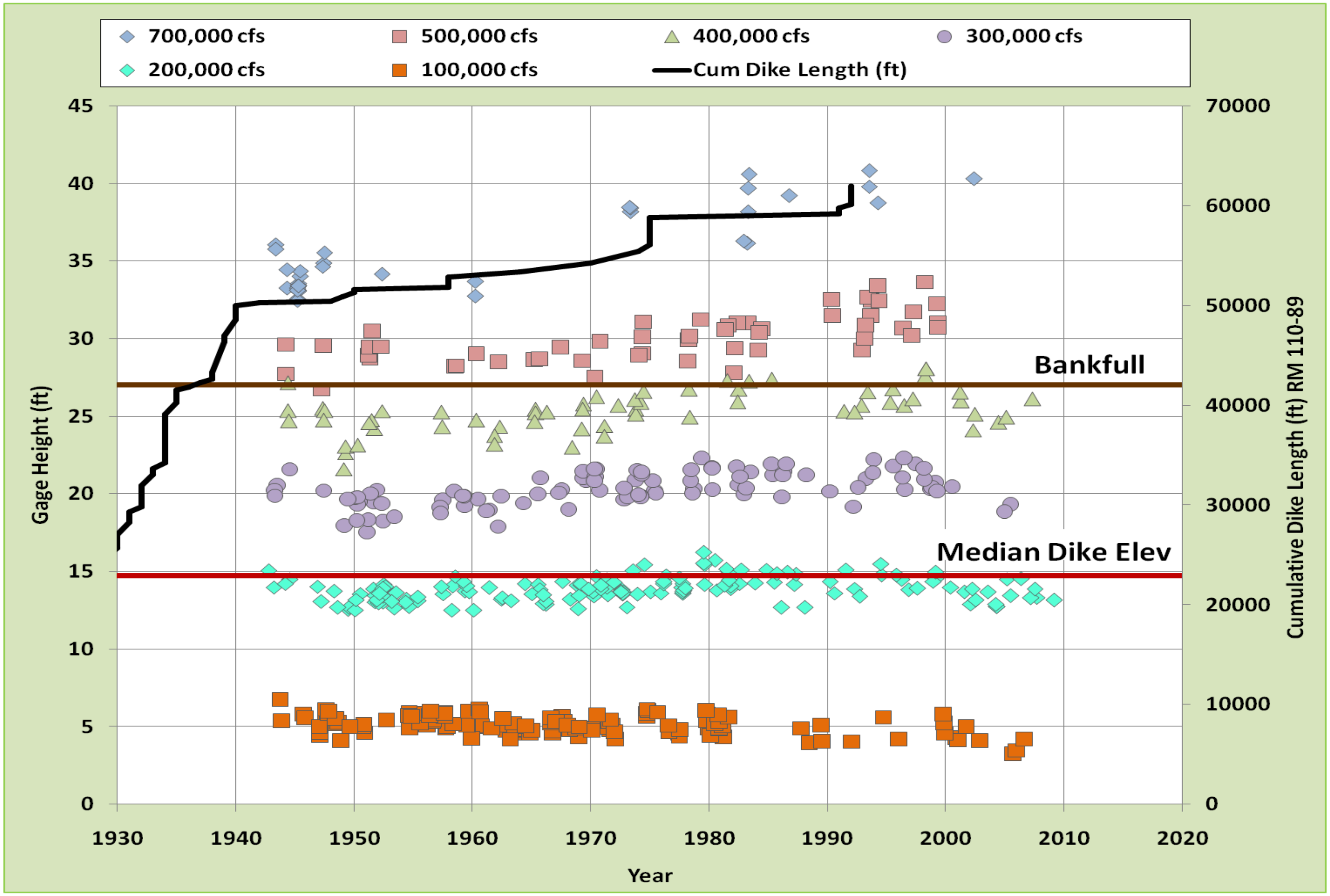

Figure **5.2 Specific gage record for the Chester gage for the period 1942 to 2009.**

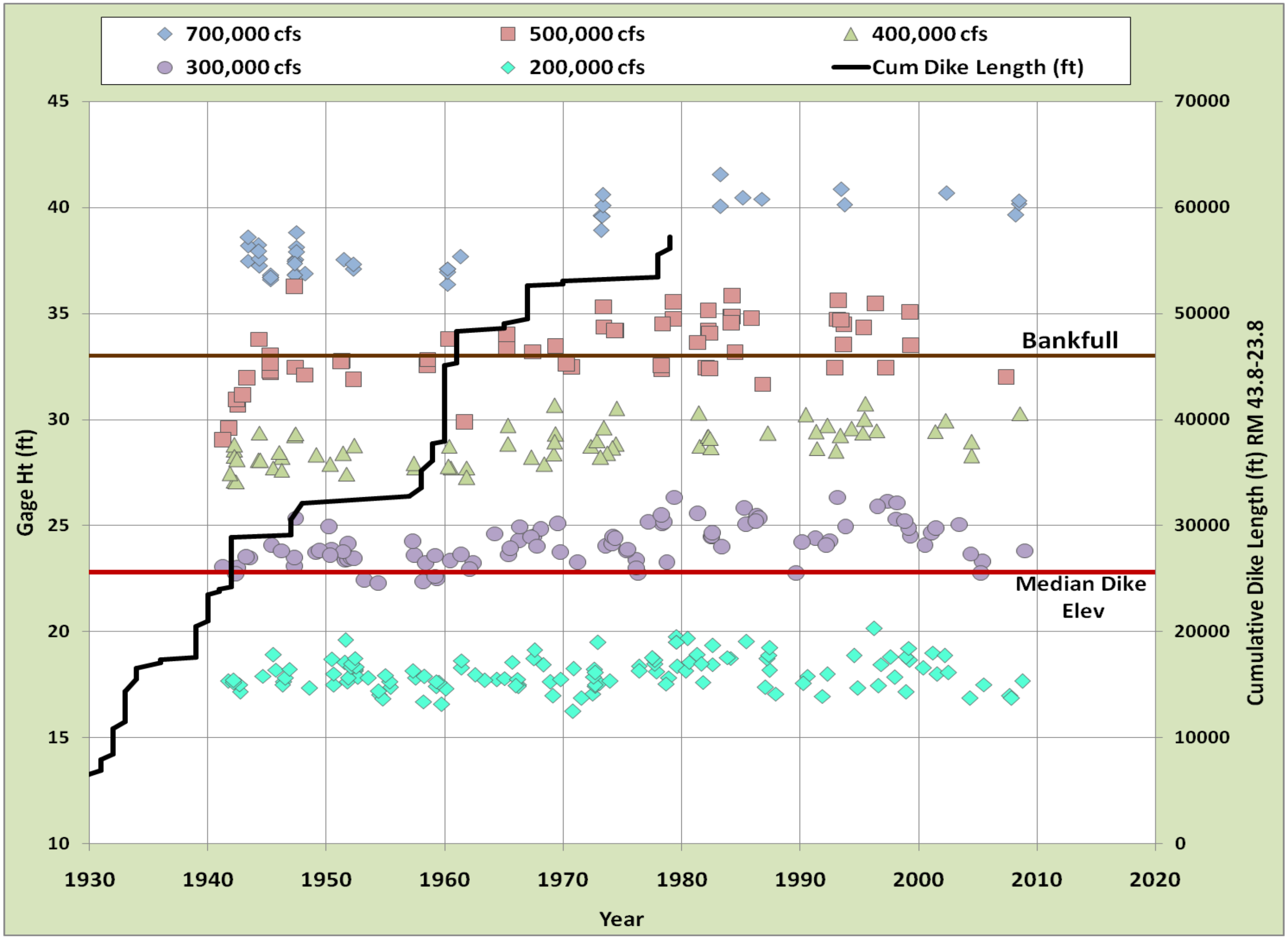

Figure 5.3 Specific gage record for the Thebes gage for the period 1941 to 2009.

Table 5.1 Summary of stage trend analyses at St Louis, Chester, and Thebes

Station	Flow 1000 cfs	Trends During Time Period											
		Pre 1973				1973-2009				Entire Period			
		Stat Trend*	R^2	Overall Trend**	Cum Dike Length (ft) ***	Stat Trend*	R^2	Overall Trend**	Cum Dike Length (ft) ***	Stat Trend*	R^2	Overall Trend**	Cum Dike Length (ft) ***
St Louis 1933-2009	100	(-) S	0.43	***SDT***	14,615	(-) S	0.51	***SDT***	7,001	(-) S	0.351	***SDT***	21,616
	200	(-) S	0.24	***SDT***		(-) S	0.26	***SDT***		(-) S	0.19	***SDT***	
	300	(-) S	0.11	***NT***		(+)NS	0.0002	***NT***		(-) NS	0.019	***NT***	
	400	(-) S	0.21	***NT***		(+) NS	0.0003	***NT***		(-) NS	0.059	***NT***	
	500	(-) S	0.20	***NT***		(+) NS	0.014	***NT***		(+) NS	0.003	***NT***	
	700	(-) NS	0.17	***NT***		(+) NS	0.0012	***NT***		(+) SI	0.124	***NT***	
Chester 1942-2009	100	(-) S	0.11	***NT***	27,183	(-) S	0.33	***NT***	7,721	(-) S	0.182	***SDT***	34,904
	200	(+)NS	0.03	***NT***		(-)S	0.11	***NT***		(+)S	0.058	***NT***	
	300	(+)SI	0.13	***NT***		(-)NS	0.002	***NT***		(+)S	0.24	***SIT***	
	400	(+) NS	0.008	***NT***		(-) NS	0.008	***NT***		(+) S	0.246	***NT***	
	500	(-)NS	0.002	***NT***		(+)S	0.31	***IT***		(+)S	0.47	***IT***	
	700	(-) NS	0.031	***NT***		(+) NS	0.22	***SIT***		(+) S	0.776	***IT***	
Thebes 1941-2009	200	(-) NS	0.002	***NT***	46,535	(-) SI	0.08	***NT***	4,200	(+) SI	0.035	***NT***	50,735
	300	(+)SI	0.076	***NT***		(+)SI	0.004	***NT***		(+)S	0.23	***NT***	
	400	(+) SI	0.118	***NT***		(+) NS	0.066	***NT***		(+) S	0.375	***SIT***	
	500	(+)SI	0.13	***NT***		(-)NS	0.018	***NT***		(+)S	0.28	***SIT***	
	700	(-) NS	0.09	***NT***		(+) NS	0.050	***NT***		(+) S	0.663	***IT***	

***** 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.

5.1 St. Louis Specific Gage

The specific gage record for the St Louis gage for the time period 1933 to 2009 is shown in Figure 5.1. 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 5.1). As indicated in Figure 5.1, 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 in Figure 5.1 is a plot of the cumulative dike length constructed in the 20 mile reach of river between RM 180 and RM 160. A summary of the analysis of stage trends is shown in Table 5.1. As indicated in Figures 5.1 and Table 5.1, 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 5.1, the stages in the post-1993 period had returned to about the same levels as prior to 1993.

5.2 Chester Specific Gage

The specific gage record at the Chester gage covers the time period from 1942 to 2009 and is shown in Figure 5.2. The same flows used at St Louis are shown at Chester. The bankfull elevation at the Chester gage is about 27 feet. A summary of the trend analysis at Chester is shown in Table 5.1. When the entire time period from 1942 to 2009 is considered, there is a slight decreasing trend in the 100,000 cfs flow. However, at 200,000 cfs there is no discernible trend. At 300,000 cfs, there appears to be a slight increasing trend, although the R^2 is only 0.24. No trend was observed at 400,000 cfs. An increasing trend was observed at both the overbank flows (500,000 cfs and 700,000 cfs). It should be noted that even though the 700,000 cfs flow had fewer data points than the 500,000 cfs flow, it had a much greater R^2 value (0.77 versus 0.47). A closer examination of the curves suggests that the trend analysis should be separated into the pre-1973 and post-1973 periods. As shown in Table 5.1, prior to 1973, there were no significant trends at any flows. In the post-1973 period, there were no trends at the in-bank flows (400,000 cfs and less). Increasing stage trends were observed at the 500,000 cfs and 700,000 cfs flows, however, the R^2 values of 0.31 and 0.22, respectively are very low.

5.3 Thebes Gage

The Thebes gage is located about 43 miles upstream of the confluence with the Ohio River and is consequently subject to backwater effects at many flows. For this reason it was necessary to attempt to remove as many of the backwater impacted flows as possible. Measurements at Thebes were checked against the corresponding stages at Cairo and if the stage differential between the two gages was less than 15 feet, then the measurements were eliminated from the analysis. Figure 5.3 shows the specific gage record for the Thebes gage. The flows used for the specific gage analysis ranged from 200,000 cfs to 700,000. The bankfull stage at Thebes is about 33 feet.

Examination of Figure 5.3 and Table 5.1 reveals no significant stage trends at the low flows (200,000 cfs and 300,000 cfs) during the 1941 to 2009 time period. At the 400,000 cfs and 500,000 cfs flows the stage appears to be increasing slightly during this time period, although the R^2 values are only 0.37 and 0.28, respectively. At 700,000 cfs, the increasing trend is more dramatic, and the R^2 value is 0.66, indicating a stronger relationship between stage and time. However, closer examination of the data indicates that these are not continuously increasing trends, but rather reflect a shift in stages in the early 1970s. Therefore, assessing the stage trends over the entire time period (1941-2009) may be misleading. When the data is analyzed for the pre-1973 and post 1973 time periods, no significant stage trends are observed before or after 1973 (Table 5.1). Thus, the stages at Thebes have been stable for the past 36 years. This is a good example of the problems that can arise when a specific gage record is interpreted over too long a time period, and major shifts in the data are ignored.

5.4 Impacts of River Engineering Structures

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).

There is considerable variation in the dike designs that have been constructed in Middle Mississippi River. In particular, the elevation of the dikes can vary significantly. Figure 5.4 shows a valley cross section just downstream of the Chester gage at about RM 103.5. The approximate location of the cross section is shown In Figure 5.5. Also shown in Figure 5.4 is the levee and a dike section typical of those in this reach. As shown in Figure 5.5, the width of the floodplain has been decreased significantly as a result of the levees in this reach. For this reach, the pre-levee valley width averaged about 4.7 miles, while the post-levees width is only about 1.3 miles, or a reduction of about 73%. Similar decreases in the floodplain width have occurred throughout the study reach.

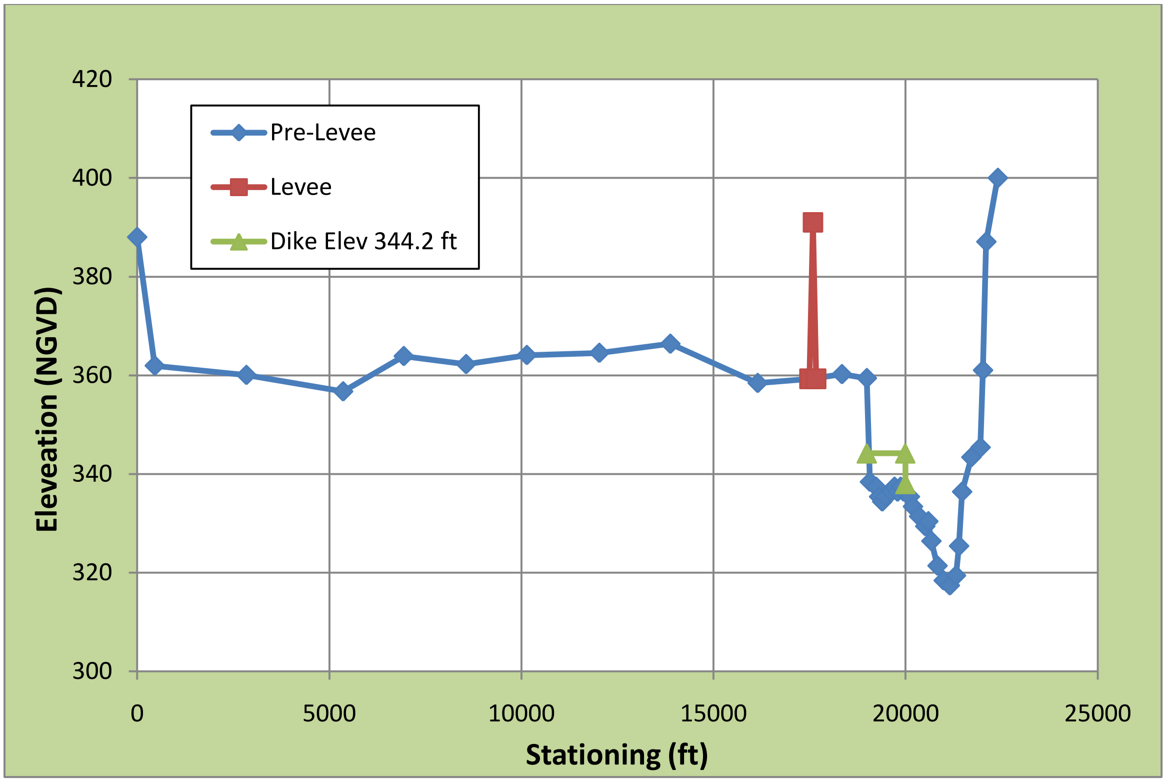

Figure 5.4 Valley cross section near RM 103.5 downstream of Chester IL

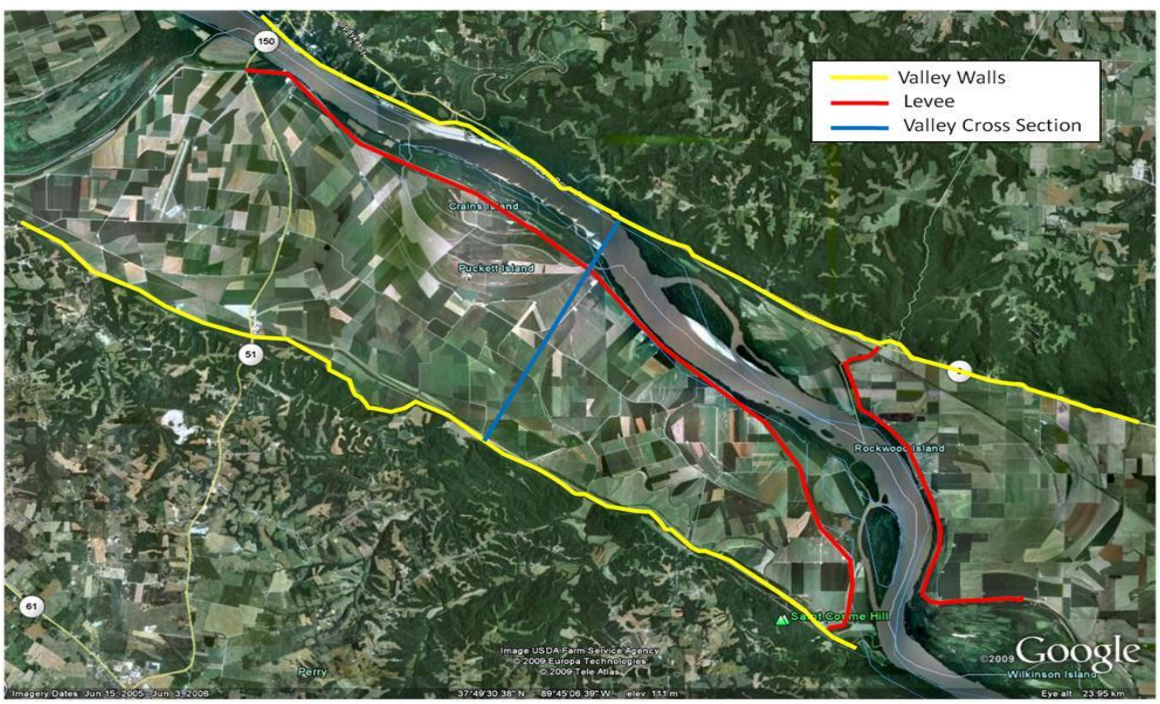

Figure 5.5 Location of valley cross section downstream of Chester

Dike elevation information relative to the gages at St. Louis, Chester, and Thebes was obtained from a St. Louis District report prepared in 1976 (USACE 1976). Table 5.2 shows the minimum and maximum elevation of dikes as well as the 25%, 50%, and 75% values. For example, for the St. Louis reach, 50% of the dikes have a height of 13.9 feet on the St Louis gage, and all dikes are less than or equal to 23.0 feet. The approximate top bank elevations at each gage are also shown in Table 5.2. The relationship between the median (50%) dike elevation and the bankfull elevations for each gage are shown in Figures 5.1, 5.2, and 5.3. As indicated by these figures and Table 5.2, the top elevation of the dikes is well below the top bank elevations. Therefore, the most dramatic impacts of the dikes should be in the low to moderate stages below top bank.

Table 5.2 Elevation frequency of dikes in the Middle Mississippi River

Percent of dikes with top elevation at or below gage height	St Louis Gage Height (ft) Reach extends from St. Louis to Chester	Chester Gage height (ft) Reach extends from Chester to Thebes	Thebes Gage height (ft) Reach extends from Thebes to Cairo
0%	4.0	6.0	10.3
25%	12.7	10.54	18.8
50%	13.9	14.7	22.8
75%	17.3	18.61	24.7
100%	23.0	23.2	27.4
Top Bank Elevation	30.0	27.0	33.0

The specific gage records at St. Louis, Chester and Thebes track 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. Each gage is discussed separately.

The cumulative length of dikes built within a 20 miles distance downstream of each of the three study gages is shown in Table 5.1. As shown in Table 5.1, between 1930 and 2009, the total length of dikes built in the St. Louis, Chester, and Thebes reaches is 21,616 feet, 34,904 feet, and 50,735 feet, respectively. The dike lengths for the pre- and post-1973 time periods are also shown in Table 5.1. A plot of the cumulative dike length is also plotted on the specific gage records at each gage (Figures 5.1, 5.2, and 5.3).

St. Louis Gage - Examination of Figure 5.1 and Table 5.1 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, yet there were no increases in stage 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.

Chester Gage - As shown in Table 5.1, there were 27,183 feet of dikes built in the Chester reach between 1930 and 1972. During this same time period no stage trends were observed at any flows (Figure 5.2 and Table 5.1). Thus, the construction of over five miles of dikes in this 20 mile reach apparently had no impact on the river stages. In the post-1973 period there was an additional 7,721 feet of dike constructed. For the in-bank flows (100,000 cfs to 400,000 cfs), at which dikes would be expected to have the greatest influence, there were no stage trends observed. At the overbank flows (500,000 cfs and 700,000 cfs), increasing stage trends were observed.

Thebes Gage - There were 46,535 feet of dikes built in the 20 mile reach downstream of the Thebes gage during the period 1930 to 1972 (Table 5.1). During this same period, there were no observed stage trends at any flows. This amounts to the construction of over eight miles of dikes without any observed stage trends in the river. There were an additional 4,200 feet of dikes built in the post-1973 period, yet no stage trends were observed.

6.0 Conclusions

An analysis of the specific gage records at St. Louis, Chester, and Thebes was conducted to identify any 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, to 1942 at Chester, and to 1941 at Thebes 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 inconsistency with respect to the location of the discharge range introduces another level of uncertainty.
    3) There is insufficient measured data at the higher flow ranges to produce reliable specific gage records.

4) The post-USGS period (1933 at St Louis and early 1940s at Chester and Thebes) provides a 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.
- At Chester for the period 1942 to 2009, there was a slight decreasing trend at 100,000 cfs, a slight increasing trend at 300,000 cfs, and no significant trends at 200,000 cfs or 400,000 cfs. Increasing stage trends were observed at both 500,000 cfs and 700,000 cfs.
- At Thebes for the period 1941 to 2009, there were no significant trends at 200,000 cfs and 300,000 cfs, while slight increasing trends were observed at 400,000 cfs and 500,000 cfs. An increasing trend was observed at 700,000 cfs.
- Upon close examination of the specific gage trends, it was observed that the apparent long term trends were not continuous, but rather a shift in stages occurred in the early 1970s. For this reason, stage trends identified for the entire period from 1930s to 2009 can be misleading. Breaking the period into Pre-and Post 1973 may provide a more realistic understanding of the system.
- Prior to 1973 (a time period covering about 40 years at St Louis and 30 years at Chester and Thebes), there were 2.8 miles, 5.1 miles, and 8.8 miles of dikes constructed within a 20 mile reach downstream of the St. Louis, Chester and Thebes gages, respectively. During this time there were no increasing stage trends observed at any flows at the three gages. 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, Chester, and Thebes reaches was 1.3 miles, 1.5 miles, and 0.8 miles, respectively. 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. At Chester, increasing stage trends were observed for the overbank flows of 500,000 cfs and 700,000 cfs.

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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