The Limitations of Using Specific Gage Analysis to Analyze the Effect of Navigation Structures on Flood Heights in the Middle Mississippi River

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Abstract

Since the construction of the first navigation structures in the Middle Mississippi River, people have been concerned about their potential effect on water elevations and public safety. To address these concerns, the U.S. Army Corps of Engineers has conducted a number of studies over the past seventy years to help understand the potential impacts river training structures. Over the past thirty five years, scientists have again questioned the effect of river training structures on flood heights in media such as papers in scientific publications, newspapers and press conferences. The basis of these claims is the use of specific gage analysis. This paper This paper analyzes the use of specific gage analysis as a means to study the effect of navigation structures in the Middle Mississippi River using the St. Louis gage as a case study. A critical examination of specific gage analysis will be conducted focusing specifically on the assumptions made and the quality and significance of the data used.

Keywords: Specific Gage Analysis, Rating Curves, Discharge, River Training Structures, Floods

BACKGROUND

Study Location

The gaging station at St. Louis (station 0701000, hereinafter referred to as the "St. Louis gage") is located on the Eads Bridge at Mile 180.0 on the Middle Mississippi River (MMR). The Middle Mississippi River extends from the mouth of the Missouri River at river mile (RM) 195.0 to the Mouth of the Ohio River at RM 0.0. The primary tributaries that affect the river at the St. Louis gage are the Missouri River and the Illinois River, which are 15 miles and 38 miles upstream respectively. The St. Louis gage is also affected by the dams upstream on the Missouri River and the locks and dams on the Mississippi River. The closest locks and dam is Locks 27 and the Chain of Rocks low water dam which is approximately 10.3 miles upstream. The Mississippi River at St. Louis can also be affected by backwater from the Meramec River at RM 161.0.

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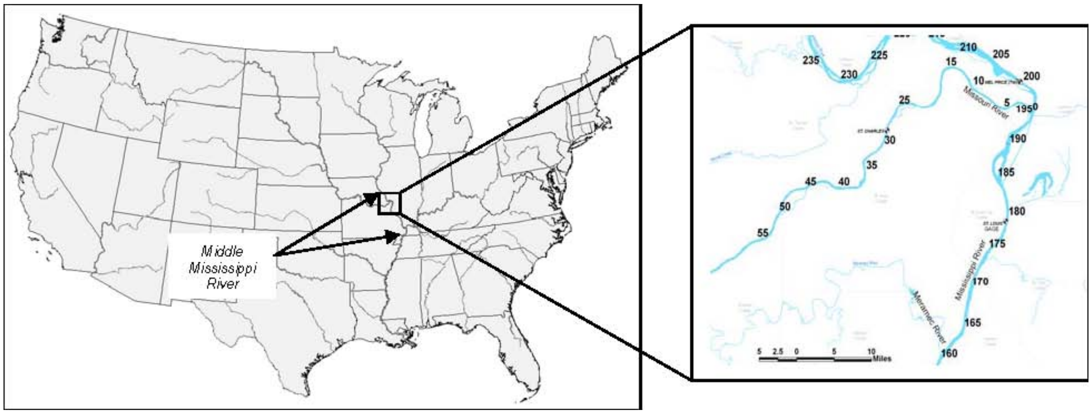

FIGURE 1: Vicinity Map

Specific Gage Analysis

Specific gage analysis can be defined as a graph of the stage for a specific discharge at a particular gaging station plotted against time. Specific gage analysis has been used to attempt to determine the historical stability of a river system by studying the relationship between stage and discharge over time. A specific gage analysis may be performed using rating curves and interpolating a stage for selected discharge, or by using actual discharge records and plotting stage for a discharge in a certain range about the selected value; possibly 2%.

The first step when using the rating curve method of specific gage analysis is to establish a rating curve for the gage being analyzed. A rating curve is a plot of stage versus discharge (Figure 2). Since rating curves are dynamic in nature, a graph should be determined for each year in the period of record. A regression curve should then be developed and plotted on the graph. The regression curve can be fit by "eye" or developed using a curve fitting technique. Since the rating curve is developed using observed data, it is only valid for the range of observed data points. It is important that the regression curve does not extend beyond the observed data points.

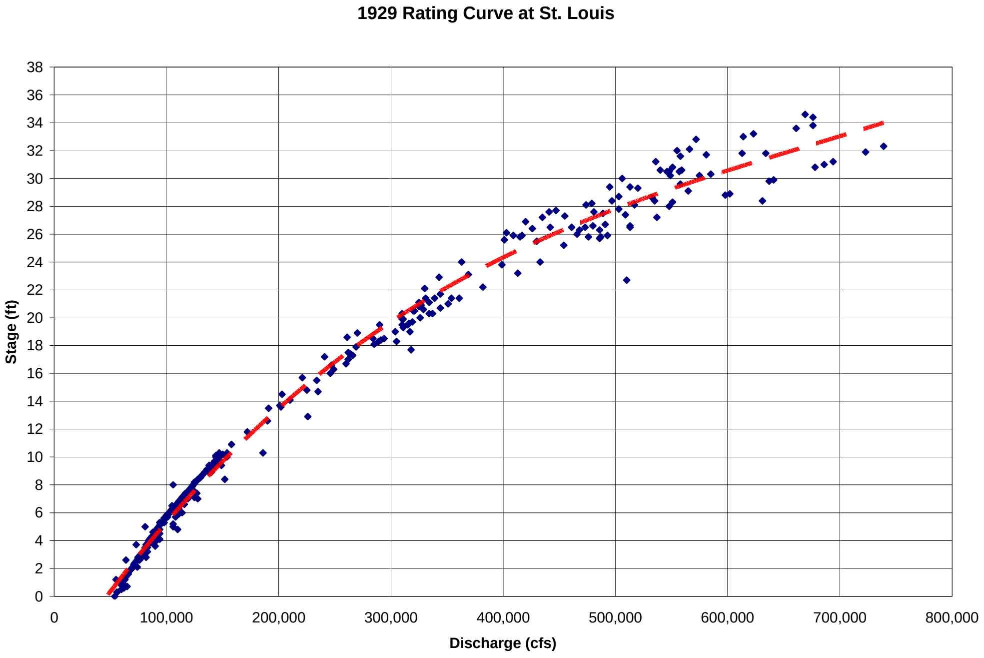

FIGURE 2: Typical Rating Curve

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Once a relationship is established through the regression curve, the discharges to be used for the analysis must be selected. Because the behavior of high and low flows can be different, it is recommended that the selected discharges represent the entire range of observed flows. For the rating curve method, the stage for each discharge is then determined for each year's rating curve using the regression curve of the graph. These stages are then plotted over time in an attempt to determine the overall stability of the river at that location (Figure 3). If using the actual discharge method, the stages are plotted against time for the discharge ranges being studied.

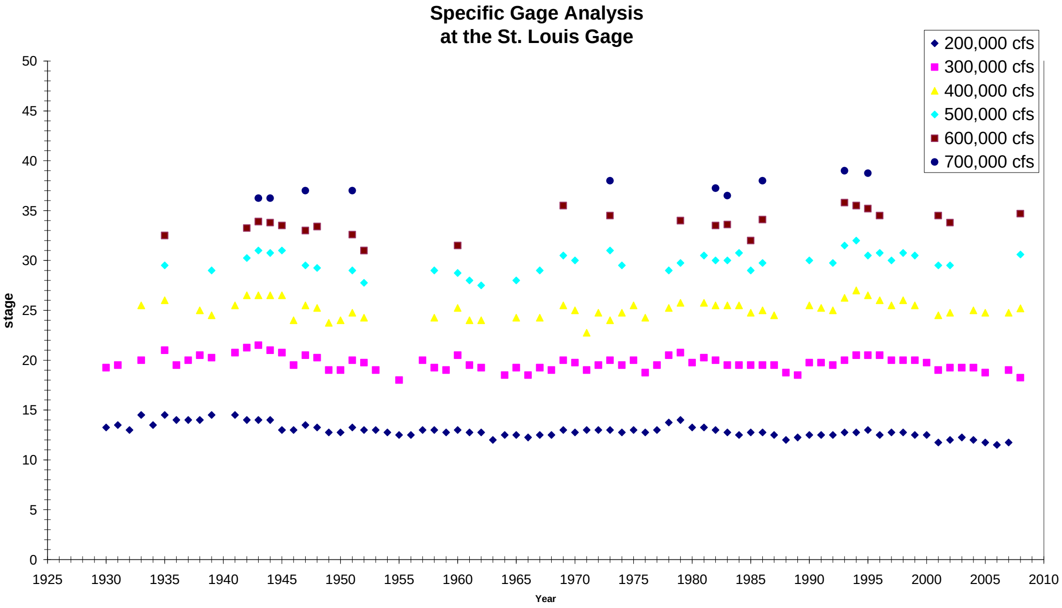

FIGURE 3: Typical Specific Gage Analysis (Rating Curve Method)

PROBLEMS ASSOCIATED WITH USING SPECIFIC GAGE ANALYSIS

Many variables can impact the rating curve and therefore the specific gage analysis. In the Demonstration Erosion Control Design Manual (1999), Biedenharn cautions the reader on the use of specific gage analysis. "The development of a specific gage [analysis] is a simple, straightforward procedure. However, the interpretation of specific gage records is more complex (1)". It is important to understand these variables and account for them when conducting a specific gage analysis.

Source Data

It is essential in any specific gage analysis to have a homogeneous data set of discharge measurements. This is relatively simple at gages that were established after the implementation of the Price current meter as the standard in 1933. If using data that predates the use of the Price current meter, it is important to have an understanding of the history of data collection of stage, cross section and velocity.

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Stage

Stage is the most straightforward measurement collected on the river because it is simply the elevation of the water measured on a gage. The first documented stage reading on the Mississippi River at St. Louis was taken in 1843. From 1843 until 1861, stage measurements were taken intermittently. Since 1861 daily stage readings have been continuously recorded.

Cross Section

Early cross sections, and more importantly depths, were measured by simply using a rod. A later measurement method was a sounding line with a weight attached. In the 1960's the U.S. Army Corps of Engineers began using single beam transducers to measure river depths. Single beam transducer systems measure the elapsed time it takes for an acoustic pulse to travel to the river bottom and back. In the 1990's multi beam swath survey technology was introduced to measure water depths. Multi beam surveys provide extremely high resolution surveys by using a series of standard single beam transducers vertically mounted on a boat. Another great improvement to river surveying technology was the introduction of Global Positioning System (GPS). GPS uses satellites to determine the position of the receiver with sub-meter accuracy without having to use any other survey equipment.

Until the use of transducers, the error associated with measuring depth on large rivers increased at higher depths and velocities. This error came from the increased bed movement at higher discharges and the limitations of using a line and weight. In high velocity and/or depth conditions the meter and weight were carried downstream. This resulted in a measured depth reading greater than the actual depth. Another source of error at higher discharges was that it was difficult for the surveyor to "feel" when the weight hit the bottom, which gave a false interpretation of the bottom and an inaccurate cross section.

Velocity

The most difficult physical characteristic to measure on a river is velocity. Historically velocity has been measured using a number of different methods, each having their own strengths and weaknesses. The five predominant velocity measuring instruments were the surface float, double float, rod float, current meter, and Acoustic Doppler Current Profiler.

The first instrument used to measure velocity was the surface float (Figure 4b). The surface float was simply a piece of material that floated on the water surface. An upgrade to the surface float was the double float (Figure 4c). The double float was a subsurface float attached to a surface float by a piece of twine. The length of twine was adjusted to fine-tune the depth of the subsurface float to determine a point velocity at any depth. To measure the velocity, the streamgager would measure the time it took for the float to go a known distance, usually 800 feet; 400 feet above and below the main discharge range. The accuracy of surface and double floats was dependent on the uniformity of the velocities throughout the length of the runs. Another limitation was that floats were largely affected by wind and other natural elements. The surface velocity measured by the surface float needed to be corrected for wind and then converted to mean vertical velocity.

Rod floats were wooden poles with a two- to three- inch diameter and a length sufficient to span the depth of the stream. To keep the rod floating upright and permit flotation at a specific depth weights were attached to the end of each rod float. Corrections needed to be applied to the raw data collected by rod floats to determine mean vertical velocity.

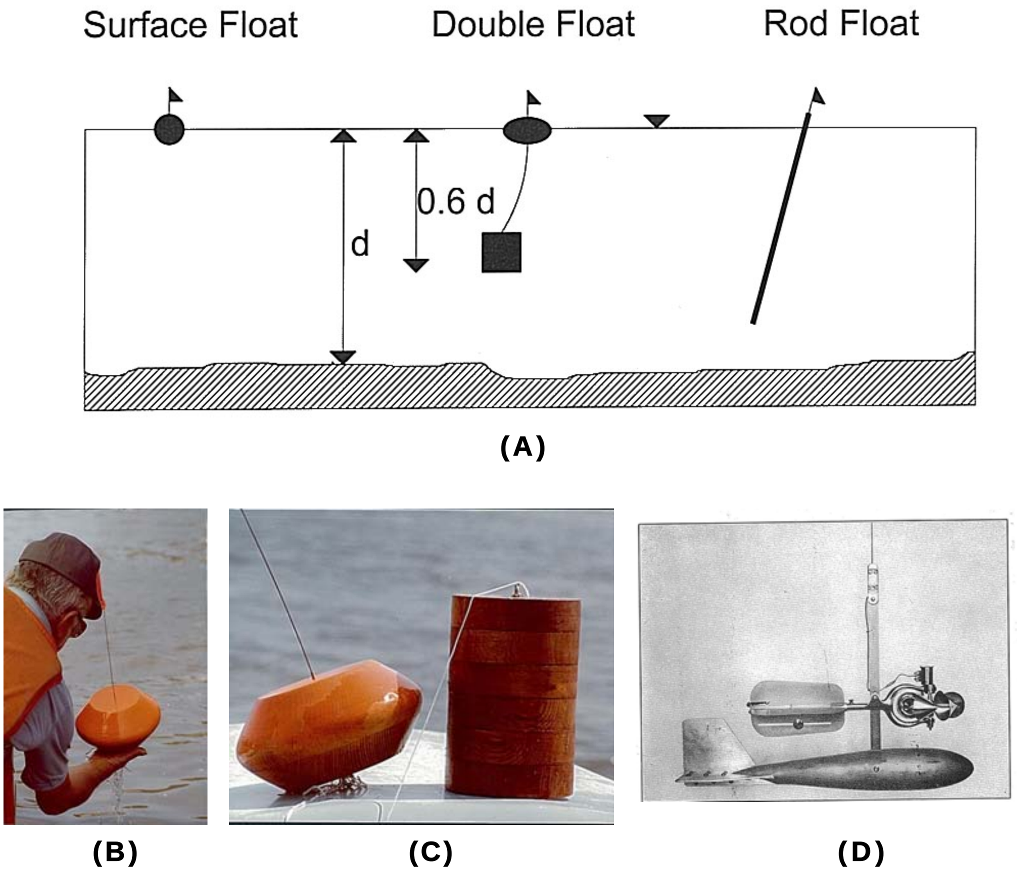

FIGURE 4: (A) Types of Floats, (B) Surface Float, (C) Double Float, (D) Price Current Meter

An upgrade to floats was the invention of the current meter. Early meters were used to measure velocity on the Mississippi River with varying results. The Price current meter, developed by William Gunn Price, was superior to other early current meters because it worked in the silt-laden water of the Mississippi (Figure 4d). With minor modifications, the Price current meter became the standard for velocity measurement from the 1930's to the 1990's. It has been widely acknowledged that the Price current meter is a superior device compared to previous velocity measuring instruments. In 1943 Grover and Harrington observed that "the current meter has a definite superiority over the other two devices for measuring discharge in that all observations of velocity and cross-sectional area pertain to a single selection, whereas a float or slope area measurement of discharge in a natural channel has at best only such accuracy as may be obtained where the observations are made in a reach of channel which is never uniform either in area of cross section or in the velocity of any thread of current throughout its length, and which the average cross section can never be known accurately even through several or many cross sections may be measured, and in which the average velocity may not apply strictly to the average cross section thus determined" (2).

The most contemporary method of measuring discharge is by the use of ADCP. ADCP is a type of sonar that measures water current velocities over a range of depths. Although ADCP is the best and most accurate technology available, the measurements are not one hundred percent accurate in all conditions. Discharge measurements have an error bar based on the quality of measurement. Measurements are categorized by excellent, good, fair and poor and adjusted accordingly. Another limitation of ADCP is that it is boat-based, which makes it difficult to make repeatable velocity measurements along the same cross section.

Discharge

Since discharge is calculated by multiplying velocity by the cross-sectional area, the accuracy of the discharge measurement is directly related to the accuracy of the instruments used to measure velocity and cross-sectional area. The first documented discharge measurement taken at St. Louis, according to data published by the Mississippi River Commission, was on August 4, 1866 by the City Engineer of the City of St. Louis, Mr. Homer. The method used to determine velocity was a surface float.

The U.S. Army Corps of Engineers started taking regular discharge measurements in May, 1872. The methodology used in the early discharge measurements varied depending on the season and person taking the measurements. For instance, in February and March of 1881, seven discharge measurements were taken using ice cakes as floats. Between October 14, 1881 and September 20, 1919 discharge was measured approximately four hundred times with rod floats. Around the same time period, October 1881 and December 1930, discharge was measured 104 times using double floats. Prior to January 1882, thirty-two discharge measurements were taken at St. Louis with early current meters. The Price meter measurements taken by the U.S. Army Corps of engineers were taken using the large Price current meter attached either singly or doubly to a rod, with a large flat iron weight at the bottom. These measurements were made from a launch, barge or boat.

In March 1933 the United Stages Geological Survey (USGS) took over streamgaging. The instrument used by the USGS was the small type AA Price current meter. Measurements were made from the downstream side of bridges. From the 1930's until the 1990's this method was the standard used to measure velocity. Starting in the 1990's ADCP became the standard method of discharge measurement.

Comparing Data Collected Using Different Instruments

After the USGS took over streamgaging, it became apparent that there was a significant difference in the stage-discharge relationship. There existed two potential causes for this difference; a decrease in the floodway capacity of the Middle Mississippi River or an apparent decrease in flood capacity caused by a discrepancy in the accuracy of measuring streamflow by older methods and equipment. A study was conducted by the U.S. Army Corps of Engineers that directly compared the different methods and instruments used to measure discharge on the MMR. Table 1 shows the results of a direct comparison of discharges at various gage heights using double floats and old type Price current meters.

Similar findings were made in a comparison of measurements taken between techniques of the USGS and those of the Corps of Engineers. The USGS took velocity measurements using a Price meter suspended from a bridge whereas the U.S. Army Corps of Engineers used old style meters suspended from a floating plant. "The U.S. Army Corps of Engineers measurements were considerably higher than the USGS results, ranging from 4% higher at a discharge of 530,000 cfs to 15% higher at a discharge of 670,000 cfs. Extrapolations to higher flows again illustrated a continuation of this trend, with differences of 20% or more at discharges exceeding 900,000 cfs. However, the field tests made no recommendations concerning any adjustment of the historic record, which was largely the result of U.S. Army Corps of Engineers measurements until 1931."(4).

Gage Height (ft)	Floats (cfs)	Meters (cfs)	Difference (%)
20	334,000	316,000	6
22	379,000	356,000	6
24	429,000	397,000	8
26	485,000	442,000	10
28	546,000	491,000	11
30	612,000	543,000	13
32	684,00	597,000	15
34	762,000	655,000	16
36	844,000	718,000	18
38	936,000	789,000	19
39	996,000	830,000	20

TABLE 1: Comparison of Discharges Measured using Different Instruments (3)

The relationship between historical instruments and measurement methods used to measure discharge was revisited again in 1979 by Stevens and the University of Missouri-Rolla Institute of River Studies (9). Although a relationship between the different instruments was not developed, an analysis of the field data from the appendix shows an overestimation of discharges similar to those in the 1944 study.

Rating curves used to estimate daily discharge using stage data are developed using field data. An overestimation in discharges by using different measurement instruments will result in rating curves that are skewed. An example of this is shown in the results of the 1945 Mississippi River Flood Discharge Capacity report. Discharges for different stages are estimated using both USACE and USGS rating curves (Table 2).

The effect of this overestimation must be included in any type of hydrologic or hydraulics study. If a non-homogeneous data set is used in a specific gage analysis, an apparent trend will be shown in the data that does not actually exist. If uncorrected historical discharges are used for years prior to 1933 in the calibration of numerical models, the roughness coefficients necessary will be artificially low.

Stage	USGS Discharge	USACE Discharge	Difference (Referenced to USGS %)
26	415,000	424,000	2
28	465,000	474,000	2
30	518,000	540,000	4
32	578,000	620,000	7
34	642,000	716,000	12
36	710,000	832,000	17
39	840,000	1,060,000	26

TABLE 2: Comparison of Discharges at the St. Louis Gage Estimated from Rating Curves (3)

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Physical Dynamics that Influence Rating Curve

Besides the methods of measuring velocity and depth, there are physical dynamics that influence rating curves and specific gage analysis. The discharge that can pass at a specific stage is greatly affected by a number of physical dynamics including seasonal bankline vegetation, water temperature, sediment load, channel bed form at the time of measurement and the hysteresis effect.

Seasonal Bankline Vegetation

Vegetation grows on stream banklines during the spring and summer months. Following the first freeze, vegetation dies or becomes dormant during the winter months. Increased vegetation adds roughness to the banklines which reduces the capacity of the channel and impedes flow. This reduction of channel capacity means that the same discharge will pass at a higher stage. If vegetation exists within the cross section at any stage "the stage-discharge relation pertaining to that gage may vary appreciably during the growing season and the effective control will thus be unstable to a greater or less degree" (2).

A physical model study was conducted by James E. Foster and James V. Allen at the U.S. Army Engineer Waterways Experiment Station in 1979 to determine the effects of overbank vegetation on the Middle Mississippi River stages in the St. Louis to Thebes reach (RM 180.0-40.0). Through a series of tests it was shown that "if the existing overbank vegetation were allowed to develop fully in its natural state, the stages in the test reach would increase as much as 1.7 ft for the flows tested". Conversely, "if the existing overbank vegetation were to be removed, stages in the test reach would be lowered by as much as 7.6 ft" (5) The results of the physical model study showed conclusively that vegetation can have a large effect on the rating curve.

The timing of floods during the year can have an effect on aquatic vegetation. During a prolonged drought, bankline vegetation can mature and may possibly become permanent. Conversely, a series of floods can wash out the vegetation and temporarily return the stage-discharge relation to the vegetation-free condition.

Sediment Load and Channel Bed Form Roughness

Sediment load has an impact on the stage-discharge relationship. The more sediment carried by the river, the higher the stage for a particular discharge. This is especially important at the St. Louis gage because of the influence of the high and variable sediment load of the Missouri River. A flood with water predominantly from the Missouri River will pass at a higher stage than the equivalent flood from the Upper Mississippi River.

This relationship was documented by Monroe, "The stage discharge relationship at St. Louis, since 1943 is governed mainly by (a) the amount of bed material carried by the Missouri River, (b) the amount of flow contribution by the Upper Mississippi River and (c) the rapidity of rise of the flood wave" (6).

Sediment load is a variable that affects bed form. A high sediment load will accelerate the transition of bed forms. Since each bed form has a different Manning's n value, it affects the stage-discharge relationship. Monroe observed that "during the 1951 flood, the river bottom rose to crest with the flood and thereafter fell with the falling stages. Much the same conditions prevailed in 1947; however, in 1943 and 1944, from other available data, the river bottom scoured. Thus, it is believed that the bed load has great effect on the stability of the rating curve" (6).

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Water Temperature

Many laboratory tests have been conducted to determine the effect of temperature on sediment transport rates and the stage-discharge relationship. Using field data on large alluvial rivers, including the Mississippi River at St. Louis, G. B Fenwick conducted a comprehensive study on the effect of water temperature on the stage-discharge relationship and concluded that "bed resistance in large alluvial rivers increases significantly with increasing water temperature, so that a given river discharge will pass at a higher stage elevation when the water is warm than cold" (7).

This variation due to temperature has also been observed in the field. Monroe noted in 1962 that "In contrast to the summer season floods of 1947 and 1951, the spring floods of both periods, though not attaining notable heights, produced greater discharges for comparable gage heights. This same phenomenon existed in the spring (April-May) of 1952 when, at the crest of this flood, greater discharges were experienced for comparable gage heights than for all other floods. In 1945, five distinct moderate flood crests were experienced, the first beginning in March and the last ending in June, with the carrying capacity of each flood becoming less than the previous flood. The flood of 1945 had a discharge of 584,000 cfs and a stage of 35.2 whereas the flood of April/May 1952 had a discharge of 681,000 cfs and a stage of 33.6, an increase of about 100,000 cfs and a decrease in stage of 1.6 feet" (6).

Hysteresis

The Mississippi River has a looped rating curve due to the hysteresis effect. The looped rating curve is the product of the falling leg of the discharge hydrograph passing at a higher elevation than the same discharge on the rising leg. This type of rating curve is common in rivers with gentle slopes. Mr. Humphrey and Mr. Abbot observed in 1876 that "It is evident that the condition of the river, whether rising or falling, makes a great difference in discharge at any given stand; but it is equally evident that a mean line between these two extremes can be drawn that shall form the basis of a table by which the annual discharge can be deduced from the recorded gauge-readings" (8). Unfortunately, with a limited number of data points at all discharges, the two extremes are not represented. Since the two extremes can not be represented by a mean line the line will be skewed one way or another. This makes comparing rating curves over time in a specific gage analysis difficult.

Number of Discharge Measurements

The number of field discharge measurements has been on the decline since the early 1980's (Figure 5). From the time the USGS took over discharge measuring, an average of 50 annual discharge measurements was taken each year. Following the 1980's, the average dropped by one half to about twenty five measurements. Since less discharge measurements are taken and the rating curve is created from a smaller sample of data, the abovementioned variables have much more effect. The unequal distribution of data points also makes it difficult to compare early rating curves to ones developed with half as many points.

The data points used in a specific gage analysis are extracted from the best fit line used to describe the rating curve. An argument could be made that the effect of the discussed variables are removed by the curve fitting process. At the lower discharges this argument is true due to the large number of observations representing these discharges used in the rating curve. At higher discharges where a smaller number of data points exist, there is not an adequate sample size to "average out" all of the discussed variables. Care must be taken to use the data points for higher discharges in context and realize that due to sample size within the rating curve they are affected by the abovementioned variables.

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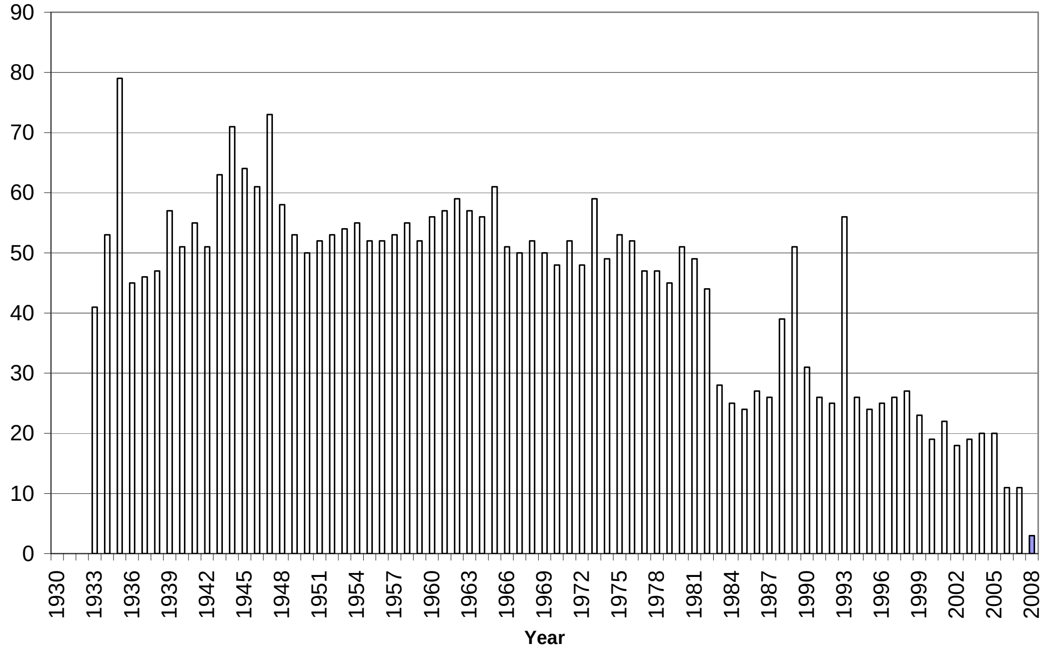

FIGURE 5: Number of Annual Discharge Measurements taken at the St. Louis Gage

ACTUAL DISCHARGE ANALYSIS

In an effort to overcome the shortcomings of specific gage analysis, actual observed discharges were studied. The idea of using measured discharges was promoted by Stevens in 1979 when he stated that "measured discharges should gain quick acceptance over estimates obtained from rating curves, because they reveal the relationship that exists between discharge and the controlling variables at the time of measurement" (9).

The data used in the actual discharge analysis was downloaded from the USGS web site. The data downloaded was a comprehensive table of all discharge measurements taken at the St. Louis gage by the USGS starting on March 29, 1933. The observations were sorted by discharge and only discharges plus or minus 5,000 cfs of the target discharges were used. Table 3 shows the discharges analyzed and the number of observations. A stage as a function of time graph was produced for all of the predetermined discharges (Figure 6).

Although the actual discharges observed have the same limitations (effect of vegetation, water temperature, hysteresis, etc.), using actual data allows the data points to be studied in context. This is impossible using the rating curve method for specific gage analysis because the data points used in the stage vs. time graph are not observed data points but rather points extracted from a best fit line. A common inadequacy that exists in both the specific gage analysis data and the actual discharge analysis is the small number of data points at higher discharges. This is due to the limited number of observations that have occurred at higher discharges.

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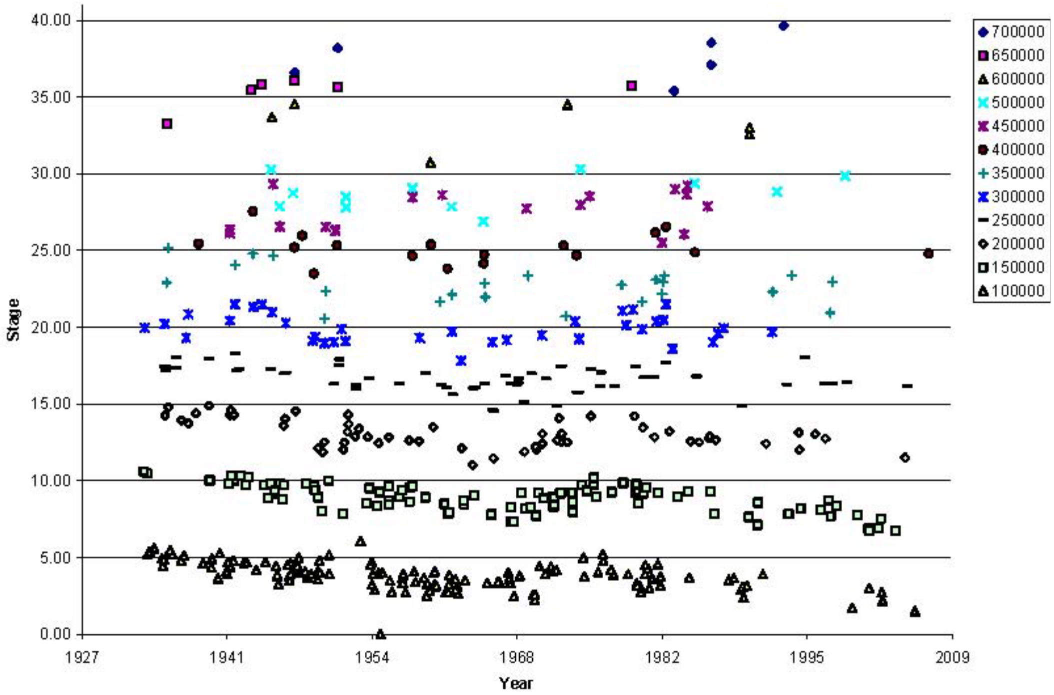

FIGURE 6: Stages for Measured Discharges at St. Louis Gage over Time

Regression Analysis

To determine if a trend exists for all of the data sets, a regression analysis was conducted on the data set representing each discharge. The calculations used in the regression analysis were done using the Analysis ToolPak in Microsoft Excel.

A hypothesis test was used to determine if time has a linear effect on stage, or that there is a slope to the stage vs. time plot. The null hypothesis tested is that the slope of the line equals zero. The p-values for 100,000 cfs, 150,000 cfs, 200,000 cfs and 250,000 cfs are very small, $p<0.05$ (Table 3) and therefore it can be said that for discharges below 250,000 cfs there is evidence to support that time does have a linear effect on stage. For discharges above and including 300,000 cfs the p-values are larger than 0.05 and a conclusion can not be made that time has a linear effect on stage.

The results of the linear regression analysis are what are to be expected from an initial look at the scatter plot of the data. At discharges below 250,000 cfs, the observed discharge values have much less variance. This could be due to the larger number of data points. It could also be the result of more favorable data collection conditions as discussed earlier in this paper.

At higher discharges, it would be very unlikely that a time dependence could be detected with fewer than ten measurements. Regardless of the method used to study if stages are rising or falling over time (specific gage analysis or actual discharge analysis), a limited number of data points at higher discharges will be a fundamental problem.

Discharge	Observations	Slope Estimate	Standard Error	t-Stat	p-Value	R^2
100000	138	-0.000076	0.7569	-7.3887	0.0000	0.2864
150000	99	-0.000082	0.7098	-7.6017	0.0000	0.3733
200000	59	-0.000065	0.7995	-4.2324	0.0001	0.2391
250000	56	-0.000046	0.8082	-2.7970	0.0071	0.1265
300000	37	-0.000019	0.9035	-0.8546	0.3986	0.0204
350000	23	-0.000065	1.1527	-1.9305	0.0672	0.1507
400000	17	-0.000014	1.0241	-0.3709	0.7159	0.0091
450000	18	0.000068	1.2298	1.4167	0.1757	0.1115
500000	13	0.000048	1.0121	1.0769	0.3046	0.0954
600000	6	-0.000041	1.5614	-0.4335	0.6870	0.0449
650000	6	0.000090	1.0051	1.1145	0.3275	0.2370
700000	6	0.000052	1.6354	0.5163	0.6329	0.0625

Table 3: Regression Analysis Results

EFFECT OF NAVIGATION STRUCTURES ON FLOOD HEIGHTS

It is important to understand that the maximum elevation of most of the navigation structures on the MMR is +15 feet on the St. Louis gage. It is also important to note that bankfull equates to +30 feet on the St. Louis gage. Above bankfull there have been a number of other physical changes that have an effect on the stage-discharge relationship.

The actual discharge analysis (Figure 6) showed that at discharges where the channel is confined within the navigation structures as well as discharges where the navigation structures are immediately submerged, a statistically significant downward trend exists between stage and time. Although the trends are not statistically significant above and including 300,000 cfs, we can make some observations that help us understand the relationship between structures and river stages.

The fact that there exists a statistically significant downward trend between stage and time for discharges when the river is confined within the navigation structures is important. It shows that the desired effect of deepening the navigation channel is being observed. Cross-section analyses on reaches where navigation structures were constructed show an increase in depth in conjunction with the decrease in width resulting in a deeper, narrower, more efficient channel.

When navigation structures become submerged, they begin acting like submerged weirs. A basic hydrodynamic principal is that backwater effects of a weir decrease as the depth of the water over the weir increases. Based on this principal, the maximum effect of navigation structures on water surfaces will be observed at the discharge where the structures become submerged. This discharge at the St. Louis gage is 250,000 cfs. The results for this discharge in the actual discharge analysis show a statistically significant downward trend between stage and time.

Although the trend for the relationship between stage and time for the next highest discharge, 300,000 cfs, is not statistically significant, a visual analysis of the data shows that there does not exist an upward trend as a result of the navigation structures. This observation can be made for all discharges up to bank full, 500,000 cfs.

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CONCLUSION

The use of specific gage analysis using rating curves is an inadequate methodology to determine the effect of river training structures on flood heights. The insufficient amount of data available at all discharges to “average out” the physical dynamics that affect the discharge that passes at a particular stage makes it impossible to compare stages extracted from rating curves. Additionally, with the lack of a relationship between field instruments, discharges taken before and after the implementation of the Price current meter can not be directly compared in any type of study.

River training structures used on the Middle Mississippi River include dikes, chevrons, and weirs. The purpose of river training structures is to change the channel geometry to utilize the existing flow energy of the river causing the channel to degrade. With the exception of bendway weirs, which are built well below the water surface at approximately negative eighteen on the St. Louis gage, all river training structures are built from twelve to sixteen feet on the St. Louis gage. Most river training structures are completely submerged at a discharge of approximately 250,000 cfs.

The amount of water over the river training structures increases as discharges increase. This increase in depth leads to a decrease in any potential effect the river training structures may have. If stage heights were increased due to river training structures, the maximum effect would be seen at discharges where the structures begin to be overtopped, or approximately 250,000 cfs. The statistical analysis of raw field measurements showed that a downward trend in stage exists at this discharge.

The results of the actual discharge analysis shows that at stages where the channel is confined within the navigation structures, the water surface elevation is decreasing over time. Combined with basic hydraulic principles, the results of the actual discharge analysis show that navigation structures do not have an effect on water surface elevations at stages where the structure is submerged. A statistically significant upward trend showing stages increasing over time does not exist. The upward trend that can be visually observed occurs for discharges where stages are above bankfull. The stage-discharge relationship at stages above bankfull is affected by a number of different variables.

REFERENCES

(1) Watson, C. D. Biedenharn. S. Scott. Channel Rehabilitation: Processes, Design and Implementation. U.S. Army Corps of Engineers. July 1999.

(2) Grover, N. A. Harrington. Stream Flow, Measurements, Records and their Uses. John Wiley & Sons, Inc. New York, 1943.

(3) U.S. Army Corps of Engineers. Mississippi River Flood Discharge Capacity. U.S. Army Corps of Engieners, St. Louis District- In House Report. March 1945.

(4) Dieckmann, R. G. Dyhouse. Changing History at St. Louis-Adjusting Historic Flows for Frequency Analysis. In Proceedings of the First Federal Interagency Hydrologic Modeling Conference. Las Vegas, NV. 1998.

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(5) Foster, J. J. Allen. Mississippi Basin Model Report 81-6: Effects of Overbank Vegetation on Mississippi River Stages in the St. Louis to Thebes Reach. Hydraulics Laboratory, U.S. Army Engineer Waterways Experiment Station. 1979.

(6) Monroe, R. Stability Stage-Discharge Curve, St. Louis District Office, USGS. 1962.

(7) Fenwick, G. Technical Report No. 6: Water-Temperature Effects on Stage-Discharge Relations in Large Alluvial Rivers. U.S. Army Corps of Engineers, Committee on Channel Stabilization. 1969.

(8) Humphryes, A. H. Abbot. Method of Gaging the Mississippi, Its Tributaries and Its Crevasses, Protection of the Alluvial Region Against Overflow and Upon the Deepening of the Mouths, (reprint of 1861 with additions). Government Printing Office, Washington, D.C. 1876. pp. 229-301.

(9) Stevens, G. SLD Potamology Study (S-3). The Institute of River Studies, University of Missouri. 1979.

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