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Effects of Federal Levees and Reservoirs on 1993 Flood Stages in St. Louis

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A physical model of the Middle Mississippi River was used to perform quantitative analyses of the effects of federal levees on flood heights. Contrary to some opinions by the general public, these tests showed that today's stage-frequency relationship at the St. Louis gage is not greatly different than that existing before the onset of changes to the river by humans, beginning in the 1820s. Federal levees result in increased flood heights upstream of the protected area, but these increases have been fully offset by reductions resulting from federal flood control reservoirs for all floods in recent years. The occurrence of the Great Flood of 1993 further confirmed these findings and continued to demonstrate the value of the federal levees and reservoirs. Federal levees are estimated to have increased flood heights at St. Louis by 0.9 to 1.2 m (3 to 4 ft) during the crest of the 1993 flood; however, federal reservoirs reduced flood levels at St. Louis by an equal amount, counterbalancing the levee increases. An estimated 19 billion dollars in flood damage was prevented by the federal levees and reservoirs throughout the Upper Mississippi and Missouri River Basins in 1993, a savings of more than the total construction cost of the projects. The model tests also found that the key historical flood discharges of the 1844 and 1903 floods, used in the design of the current levee system, may be overestimated by up to 33 percent.

St. Louis, Missouri, is one of the best known river towns in the world, popularized in Mark Twain's books about life on the Mississippi River. Although most of the city sits on high ground, well above maximum flood levels, low areas are occasionally threatened by three large rivers that join a short distance upstream of the city of St. Louis. The Illinois, the Upper Mississippi, and the Missouri Rivers form the "Father of Waters," the great Mississippi, which flows south, gathering the inflow from the Ohio, the Arkansas, the Red, and many other lesser rivers, on its long journey to the Gulf of Mexico. The river reach from the Missouri to the Ohio is designated as the Middle Mississippi River. It extends from the mouth of the Ohio (Km O) to the mouth of the Missouri River (Km 313.8, or Mile 195), with downtown St. Louis located at Km 289.7 (Mile 180). To reduce the frequent and repetitive flood damage in this reach, the St. Louis District of the Corps of Engineers had overseen construction of levee raises in the 1950s and 1960s to the privately constructed Alton to Gale (Illinois) levees. The federal levee system through this reach is shown in Figure 1. This system provides protection to the urban and agricultural flood plain areas from Km 74 (Mile 46) at Gale (just downstream of Cape Girardeau, Missouri) to Km 326.7 (Mile 203) at Alton. Four major urban levee units in the St. Louis area give protection from a river stage of 15.8 m (52 ft) on the St. Louis gage, a stage estimated as rarer than a 0.2 percent annual chance (500-year recurrence interval) event. Three of these units protect more than 40,500 hectares (100,000 acres) in the urbanized Illinois floodplain, and the fourth protects less than 1200 hectares (3000 acres) of intense commercial and industrial development in a narrow strip along the Missouri shore. These units are shown on Figure 2. The seven agricultural levee units downstream from the urban area are designed for a 2 percent annual chance (50-year recurrence interval) event. These seven units provide partial protection to more than 80,900 hectares (200,000 acres) of highly productive farmland. As seen, most of the Middle Mississippi River flood plain has a high level of protection.

Throughout the 1970s and early 1980s every flood along the Middle Mississippi River resulted in complaints by local citizen and environmental groups that the Corps had actually made flooding worse by levee construction in the area (*1,2*). Extensive complaints by residents of St. Charles County, located just upstream of the end of levee system and between the junction of the Mississippi and Missouri rivers, resulted in the initiation and completion of qualitative studies. These studies are described elsewhere (*3,4*). These qualitative studies demonstrated that federal levees had much less an effect than had previously been thought. However, additional more quantitative tests were needed to evaluate several scenarios and to better determine the effects of only the federal levee raises on flood heights near St. Louis. These tests proved invaluable as the Great Flood of 1993 unfolded, and the effect of levees on flood levels was a question asked by the news media from throughout the world. This paper describes these model tests and the results and uses these tests to focus on the effects of federal flood reduction projects on the Great Flood of 1993.

PHYSICAL MODEL TESTS

In 1985–86, a series of physical model tests was performed for the St. Louis District by the Corps' Waterways Experiment Station using the Mississippi Basin Model (MBM) in Clinton, Mississippi. It was proposed to isolate the effects of the federally raised levees on flooding by comparing flood elevations for today's conditions with those in existence in 1820, before any effects by humans (*5*), in 1940 (before any flood reduction work in the reach by the Corps of Engineers) and by comparing today's conditions with only the private levees of 1940 (no federal levees). In addition, the MBM was to be used to estimate the historical peak discharges for the 1844 and 1903 floods. These two events, neither of which was gaged at St. Louis, play a large part in flood evaluations and levee design on the Middle Mississippi.

MODEL ADJUSTMENT AND CALIBRATION

These tests required extensive updating and modifications of the MBM. Today's conditions landward of the levees were fully incor-

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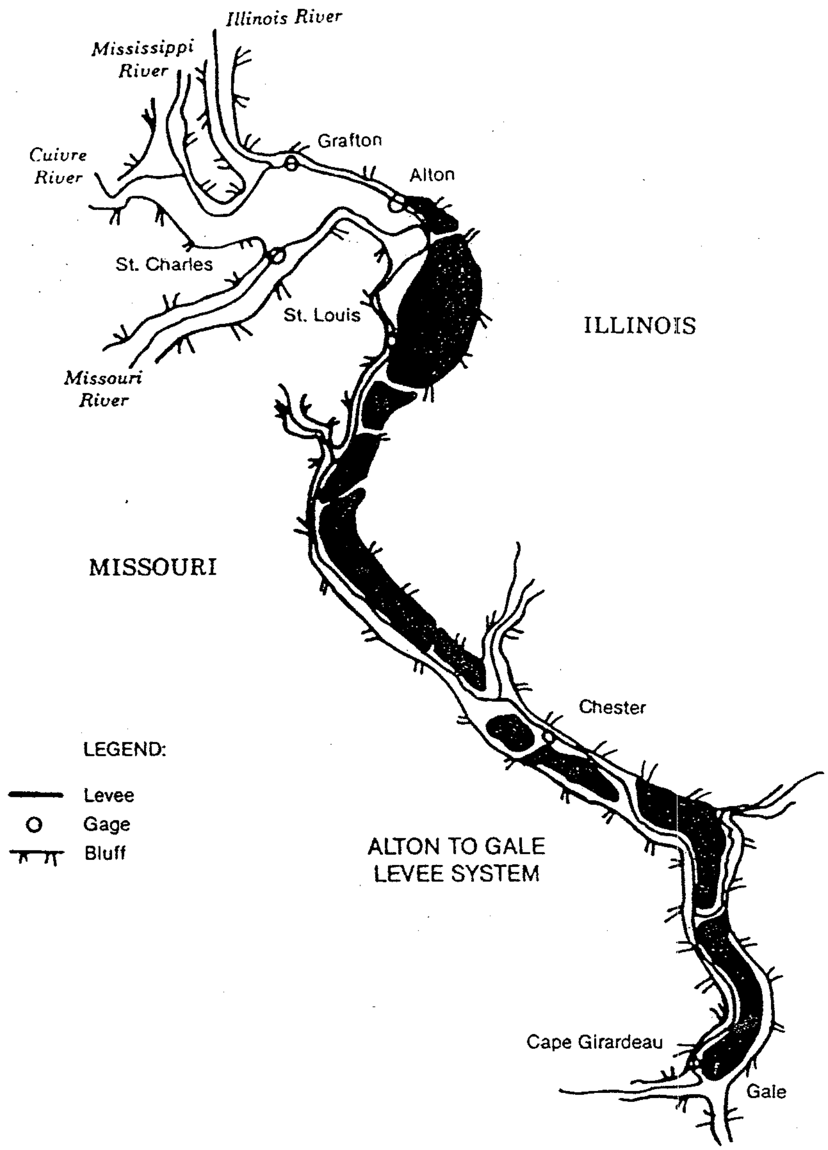

FIGURE 1 Levee location: Alton to Gale, Illinois.

porated by adding the extensive railroad and highway fills across the floodplain, adding new bridges to the model and including the extensive flood plain urbanization in the St. Louis area. The model was changed to simulate 1940 conditions by installing only the private levees in place at that time, as well as the vegetation patterns and land use of 1940, based on period maps. Finally, the 1820 condition was modeled by removing all levees and flood plain obstructions and adding the dense vegetation then prevalent throughout the flood plain. An excellent chart of the river valley, prepared in 1797 and showing the vegetation in the valley, was available to use as a guide. The channel geometry was not adjusted because earlier studies (*6*) had found that the Middle Mississippi River showed similar channel widths and surface areas as it does today. However, one reach of the main channel was modified for 1820 conditions by re-installing a 13-km (8-mi) reach of the river, about 97 km (60 mi) downstream from St. Louis that had been cutoff naturally by the river in 1888. Today's conditions (with federal levees) were extensively calibrated to known stage and discharge data for the floods of 1973, 1982, and 1983. After calibration was achieved, a series of discharges (Table 1), ranging from a 10-year recurrence interval through the estimated 1844 peak discharge (rarer than a 500-year recurrence interval event) was run for each of the four scenarios. The results were surprising.

GENERAL FEDERAL LEVEE EFFECTS

To estimate the effects of levees, local interest groups in the area had used gage records that showed higher recent levels of flooding compared with older records for the same discharge, ignoring the effects of any other changes in the system between flood years. Besides the effects of humans, the dynamics of the Mississippi River can result in significantly different river stages for a given discharge. Water temperature, river planforms, vegetation, and other features have caused stage changes of several feet for specific flood discharges. Comparing gage records alone cannot address the

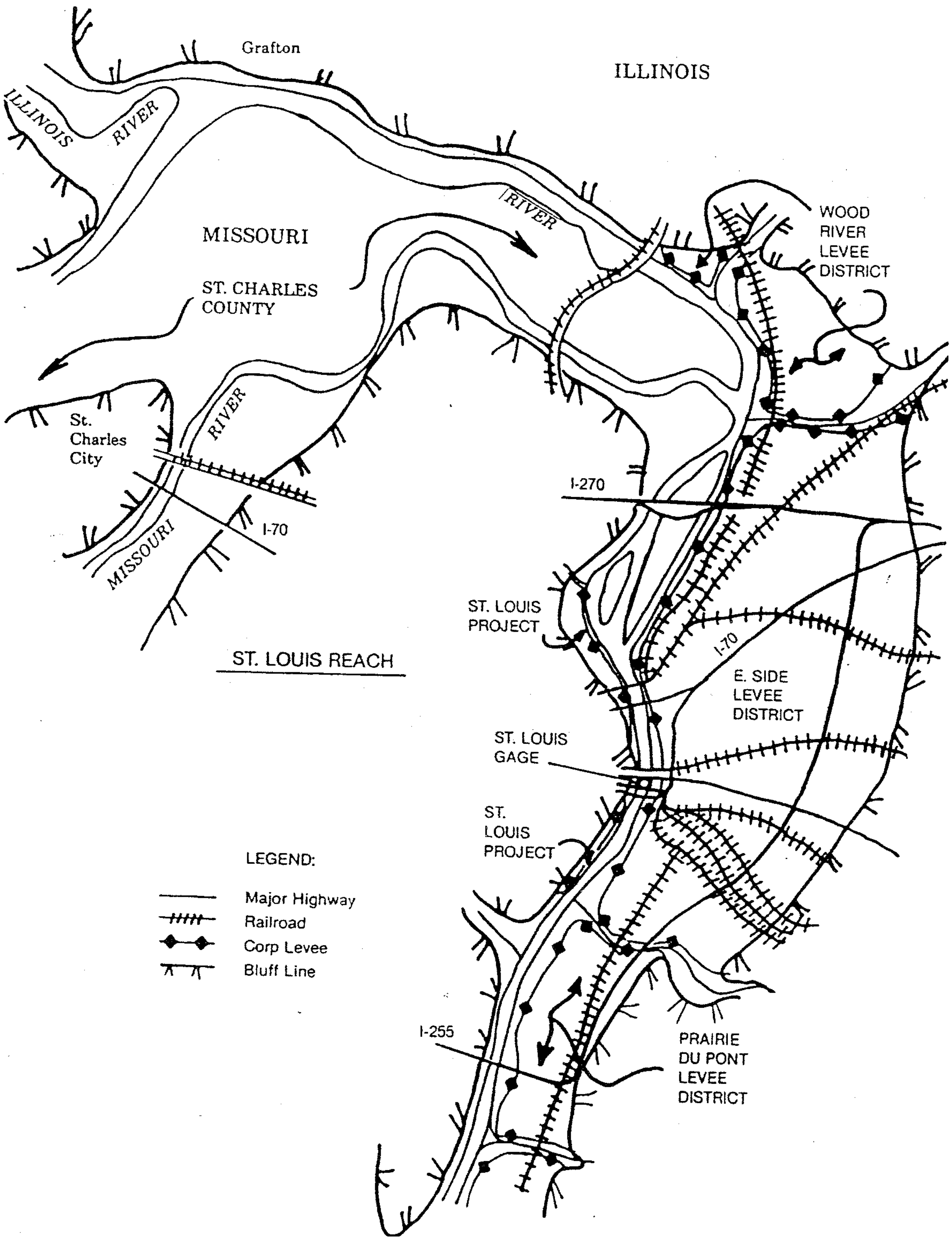

FIGURE 2 Levee location: St. Louis Area.

changes of river stage caused by only one variable: levees. The only way of determining the effects of levees alone is through the use of a physical or analytical model in which all variables are held constant except levees. This was the objective in the series of MBM tests. The MBM tests showed that the federal levees (as expected) cause increases in flooding; however, these increases were from less than 0.1 m (4 in.) to 1.2 m (4 ft) compared with 1820 conditions, depending on the discharge and location of flooding. Previous rough analyses by private citizens, based on gage record comparisons only, had sought to show that these increases were 2.4 to 4 m (8 to 13 ft). Furthermore, the increases caused by federal levee raises had been minimal for floods occurring before 1993, generally a 0.3-m (1-ft) increase maximum. The simulated 1940 land use conditions showed that stage-discharge relationships had decreased

TABLE 1 Test Discharges and Frequencies at St. Louis

Discharge (cms)	Today's Frequency	Pre-Reservoir Frequency
	Average return interval (years)	
19,540	10	5
22,220	20-25	10
26,200	50	20
28,890	100	40
34,550	300-400	100
36,820	500-1000	200

36,820 cms is the levee design discharge at St. Louis
1 m^3/sec = 35.71 ft^3/sec

compared with 1820 conditions. This change was evidently because of the extensive flood plain clearing for agriculture use that occurred continuously throughout the 1800s and early 1900s. An average reduction of about 0.7 m (2.3 ft) for moderate to severe flood discharges was shown by the model results. Flood elevation differences between today's with-levee river compared with the 1820 conditions showed increases of only 0.1 to 1.2 m (0.3 to 4 ft) in St. Louis. Although today's flood flows are constrained to a leveed floodway, ranging from about 600 to 1000 m (2000 to 3300 ft) in width for a several kilometer reach in St. Louis, the effects of this conveyance loss are not as significant as previously thought. The dense flood plain forests that were common in the 1800s evidently also limited effective flow area outside the main channel. Upstream and downstream of the narrow St. Louis reach, the average width of the floodway widens out to 2 to 3 times the width in St. Louis. Figures 3 and 4 illustrates stage-discharge relationships at the St. Louis and Alton, Illinois, gages, respectively. The frequencies shown in Figures 3 and 4 are for existing conditions only and do not apply to the 1940 or 1820 time periods, before the construction of numerous flood control reservoirs that significantly reduced the discharges associated with a specific frequency.

GENERAL FEDERAL RESERVOIR EFFECTS

Differences resulting from various land use and levee scenarios for stage-discharge relationships also do not include the effects of upstream reservoirs on the Upper Mississippi or Missouri River watersheds. The changes in discharge-frequency relationships at key gages throughout the Missouri and Mississippi River systems were first developed in the 1950s through extensive evaluation and routing of actual and hypothetical floods with and without several different reservoir scenarios. The adopted discharge-frequency relationships in St. Louis and at other nearby gages have been reevaluated on three occasions in the past 20 years and are consistent with statistical analyses performed on the data stream for St. Louis. The differences between pre- and post-reservoir conditions are pronounced, generally decreasing peak discharges at St. Louis by 15 percent or more. All significant floods on the Middle Mississippi since the 1973 event have been reduced by an average of 1.5 m (5 ft) through upstream reservoir holdouts, as shown on Table 2. The largest reduction occurred during the flood of April 1994. Peak stage at St. Louis for this event was estimated to have been up to 3 m (10 ft) higher without the reduction effects of fed-

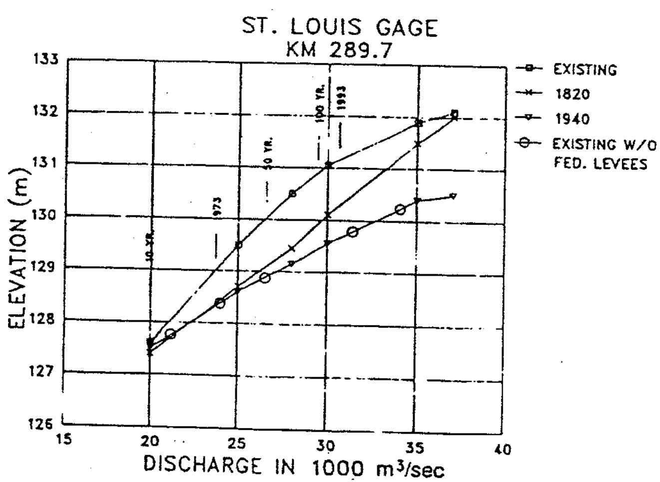

FIGURE 3 Stage discharge relationship at St. Louis Gage.

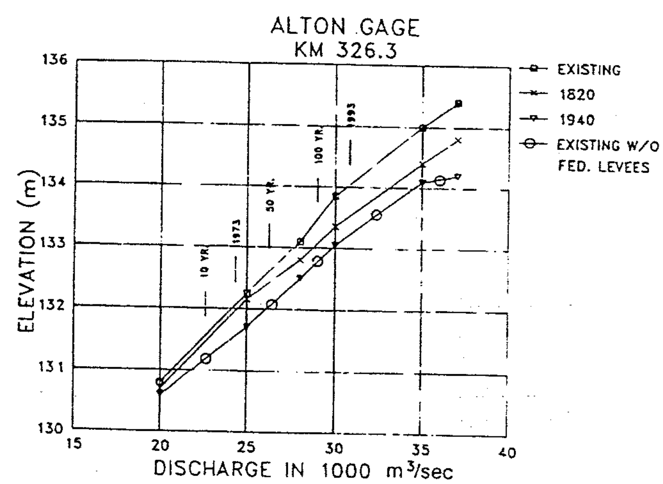

FIGURE 4 Stage discharge relationship at Alton, Illinois, Gage.

TABLE 2 Estimated Resevoir Effects at St. Louis

Flood	Approximate Decrease in Discharge (m³/sec)	Approximate Decrease in Stage (m)	Actual Stage (m)	Approximate Stage With No Reservoirs (m)
1979	3,115	0.9-1.2	11.5	12.7
1982	2,550	0.6-0.9	12.0	12.8
1983	3,965	1.2-1.5	11.1	12.3
1986	5,665	1.8-2.1	11.9	13.9
1993	9,005	0.9-1.2	15.1	16.2
1994	8,495*	2.4-3.0	11.2	13.9

Flood Stage (Bankfull) = 9.1 m (30 ft)
1 m = 3.28 ft, 1 ft³/sec = 0.0283 m³/sec

*Stage reductions are much greater for this flood because the 1994 flood would still be contained by the levee system; the 1993 flood would have overtopped all Federal urban levees in the St. Louis area, limiting the stage reductions by reservoirs.

eral reservoirs. Because of the extensive system of reservoirs, meteorological and climatological events occurring today will result in less water reaching the Missouri and Mississippi rivers at the crest of a flood compared with conditions before reservoir construction, which commenced in earnest in about 1940. When one includes both levee and reservoir effects, today's stage-frequency relationships are not much different than those of the early 1820s.

GREAT FLOOD OF 1993

The 1993 flood on the Mississippi and Missouri rivers in the Upper Midwest broke all records for stage, volume, peak discharge, duration, and frequency for more than 1610 km (1000 mi) of the two rivers and for many of their major tributaries. A sense of the magnitude of the Great Flood of 1993 can be obtained by reviewing some of the statistics at the St. Louis gage in downtown St. Louis.

- The peak stage exceeded the previous flood of record by nearly 2 m (6.2 ft).
- The discharge of 30,280 m³/sec (1,070,000 ft³/sec) is the greatest discharge ever measured during more than 130 years of site data, exceeding the previous high by 26 percent.
- Flood elevations exceeded the flood stage (bankfull capacity) of 9.15 m (30 ft) for 80 consecutive days during the main portion of the flood and for 148 days during the calendar year. The previous record was 77 days above flood stage, both consecutively and annually.
- Durations of flooding at high stages were unprecedented. The flood was 3 m (10 ft) or more over flood stage for 36 days, exceeded the "50-year flood" stage for 23 days, and exceeded the "100-year flood" stage for 8 days. Before 1993, there were only 12 days total in the entire period of record, dating back to 1861, that exceeded flood stage by 3 m (10 ft) or more.
- The total water volume passing St. Louis during the main body of the flood, from June 26 to September 13, was about 1.382×10^{11} m³ (112 million acre-ft). This volume could fill a box $1.61 \times 1.61 \times 53.3$ km high ($1 \times 1 \times 33.1$ mi high).
- The average daily stage for the 1993 calendar year approximates the average annual high stage, on the basis of more than 130 years of data.
- The frequency of the peak discharge is estimated to be a 150- to 200-year exceedance frequency at St. Louis. Some upstream stations have estimated the flood as rarer than the 500-year exceedance frequency event.

Despite these staggering statistics, the performance of federally constructed levees, floodwalls, and flood control reservoirs was outstanding and prevented most potential damage. For instance, flood damage in the St. Louis District alone is estimated as $1.4 billion; damages prevented by the federal flood reduction components are estimated at $5.4 billion. Thus, about an 80 percent reduction in potential flood damages along the 483 km (300 mi) of the Mississippi River and tributaries in the St. Louis district was achieved.

Performance of Levees

The flood overtopped or broke 1082 of 1571 levees in the watersheds of the Mississippi and Missouri rivers, upstream from the mouth of the Ohio River. Most of these levees were constructed by private or nonfederal entities and protected primarily agricultural areas, with protection levels from a 20 (5-year) to 5 percent (20-year) annual chance event. Given the severity of the Great Flood of 1993, it should not be surprising that 1043 of the 1345 private and nonfederal levees could not prevent the river from flooding the agricultural areas. Of the 226 federal levees, only 39 succumbed to the river. These 39 federal levees also were designed to protect primarily agricultural areas and offered protection ranging from a 5 percent annual chance (20-year) to a 2 percent annual chance (50-year) event. Only one of these levees failed, with the definition of a failure meaning the levee broke before the river exceeded the design river stage for the levee. Nearly all flooding of protected lands behind federal levees occurred through overtopping of the levee; only four units filled before overtopping. Of these four units, two broke because of underseepage, piping or scour when the river stage was greater than the design river stage but was less than the levee crest elevation. One filled because of human failure to operate a closure structure at a railroad opening, and one levee actually failed, broke before floodwaters reached as high as the design stage. All levees and floodwalls designed for floods of the magnitude of the 1993 event performed as expected, and no flooding resulted to protected areas. In addition, several levees designed for events less severe than the 1993 flood held through extraordinary floodfighting measures. Overall, the performance of federal levees and floodwalls was more than one could reasonably expect, given the severity of the Great Flood of 1993. These findings are in agreement with those of the Report of the Interagency Floodplain Management Review Commitee (*1*), which found that levees greatly reduced the actual flood damages but had only minor overall effects on flood stages throughout the Mississippi and Missouri River systems.

Performance of Reservoirs

The Federal Government operates more than 70 flood control reservoirs in the Upper Mississippi and Missouri watersheds, with most of these structures in the Missouri River Basin. These dams and reservoirs range from huge structures on the Missouri River main stem in the Dakotas and Montana to small structures well up in the headwaters of tributary streams. The rainfall of 1993 was very widespread, so most of these structures retained significant volumes of water, resulting in important crest reductions on both major rivers. Current estimates of reservoir effects on the Great Flood of 1993 show about a 0.9 to 1.2 m (3 to 4 ft) reduction in St. Louis. This lower stage represents a peak discharge reduction of about 9000 m^3/sec (over 320,000 ft^3/sec); the peak discharge at St. Louis would have been over 39,000 m^3/sec (1,391,000 ft^3/sec) instead of the actual 30,280 m^3/sec (1,070,000 ft^3/sec). All four urban levees in the St. Louis area probably would have been overtopped during the 1993 flood without the upstream reservoir control of this event. Throughout the Middle Mississippi, reservoir reductions of crest stages ranged from 0.9 to 1.6 m (3 to 5.1 ft). Significant reservoir reductions occurred throughout the Missouri and Mississippi rivers, also an important finding (*7*) that indicated that federal levees and reservoirs prevented more than $19 billion in flood damage during the 1993 event. As indicated by the Corps of Engineers (*8*), reservoir reductions along the Missouri River are estimated as 1.8 m (6 ft) in Sioux City, Iowa; 1.5 to 2.4 m (5 to 8 ft) in Omaha, Nebraska; and 0.9 m (3 ft) in Kansas City, Missouri, and points downstream. Upper Mississippi River reservoirs are few, and the reductions are less upstream of the mouth of the Missouri River, generally 0.1 to 1.2 m (0.3 to 4 ft) along the Missouri and Illinois border.

Contrary to some opinions, federal flood control projects have proved their value conclusively. During this century, total federal expenditures for structural flood control features have been estimated at $25 billion to $30 billion (*9*). Since 1983, Corps of Engineers projects alone have prevented $170 billion in damages (*10*). A strong case can be made for the value of flood reduction projects, showing that the entire system pays for itself about every 18 months, based on the last 10 years of data.

Joint Effects at St. Louis

For the 1993 flood peak discharge of 30,280 m^3/sec (1,070,000 ft^3/sec), the model tests suggested that the levees would result in a maximum stage increase of 1.2 to 1.5 m (4 to 5 ft), comparing 1940 conditions with today's. The difference is about 0.3 m (1 ft) less if comparing 1820 conditions, before the start of humans' modifications. The peak stage occurred in St. Louis from 0900–1000 hr on August 1 when the first of two large downstream agricultural levees was overtopped and filled. These two levees were both designed to provide protection from the 2 percent annual chance (50-year recurrence interval) event and did not actually overtop until river stages had reached about 1.2 m (4 ft) higher than the levee design river stage. Had no overtopping occurred, it is estimated the St. Louis stage would have crested about 0.3 m (1 ft) higher. With no levees existing on the Middle Mississippi River, it is estimated that river stages at St. Louis would have been 0.9 to 1.2 m (3 to 4 ft) lower. These figures were independently confirmed by a university study commissioned by a local newspaper and are similar to other findings (*11*). Although a further reduction of 1 to 1.2 m appears large, one has to evaluate the significance of this reduction. If all levees were removed, the river would still have crested at least 4.9 m (16 ft) over flood stage. However, then the river would have flowed from bluff to bluff through the St. Louis area, reaching up to 16 km (10 mi) wide at some locations. Several billion dollars in additional damages would have been caused by the flood. In addition, there would not be a significant reduction in damages elsewhere, because of the limited flood reductions attributable to levee removal. As mentioned previously, federal flood control reservoirs reduced flooding in St. Louis by about 0.9 to 1.2 m (3 to 4 ft). Thus, the flood reduction effects of reservoirs again offset the local effects of levees in St. Louis. This offsetting effect has been noted for every significant flood in St. Louis since 1973. Table 2 illustrates the effects of reservoirs on St. Louis flood peaks in recent years.

HISTORICAL DISCHARGE EVALUATION

The MBM was also used to determine a peak discharge that would reconstitute historical highwater marks from the 1844 and 1903 floods, under the appropriate land use conditions. These two floods have estimated peak discharges of 36,820 m^3/sec (1,300,000 ft^3/sec) and 28,860 m^3/sec (1,019,000 ft^3/sec), respectively, in St. Louis. The 1844 discharge is the basis for urban levee design heights in the St. Louis reach. Neither flood discharge was measured in St. Louis. After the 1903 flood, an estimate of this flood was made for St. Louis, based on measurements at gages 112 and 215 km (70 and 134 mi) downstream conducted with the crude instruments available at the time. Before 1930, velocity measurements were often made using floats (*6*). Float measurements have the tendency to overestimate river velocity and thus the total discharge. The overestimate becomes progressively worse as flood discharge increases. The 1903 peak discharge value at St. Louis was estimated by increasing (instead of decreasing) the discharge measured 113 km (70 mi) downstream with floats by about 13 percent, which appears unreasonable. The 1844 discharge at St. Louis was then estimated through ratioing the downstream gage results for the 1903 flood upward. Not included in this estimate was the fact that the river had shortened itself between the two floods through a natural cutoff in 1888, affecting both the slope and the channel storage available as well as the significant changes in flood plain land use between the two periods. There has long been a serious question about the validity of the St. Louis peak discharge estimates of 1844 and 1903 because of the significantly changed river conditions between 1844 and 1903 and the likely overestimate of flood discharges. The MBM tests found that flows much less than these official estimates gave a reasonable match of 1844 highwater marks under the 1820 land use condition. Model flows of about 24,640 m^3/sec (870,000 ft^3/sec) and 22,090 m^3/sec (780,000 ft^3/sec) for the 1844 and 1903 floods, respectively, in St. Louis resulted in the matching of 12 to 15 known highwater marks (within 1 ft or less) available for both historic floods. These model peak discharge values are about 33 and 23 percent less, respectively, than current official estimates of the 1844 and 1903 flood peaks at St. Louis and are far below the measured peak discharge of August 1, 1993 (30,280 m^3/sec or 1,070,000 ft^3/sec). Both Corps of Engineers and United States Geological Survey personnel are further reviewing these results and the historical estimates for St. Louis. This review may eventually lead to a revision of the historical records. The lower flows found by using the MBM are similar to floods occurring in the 1970s and 1980s. The April 1973 flood (24,130 m^3/sec or 852,000 ft^3/sec) held the record for peak stages throughout much of the Middle Mississippi before 1993. Peak discharge of the 1973 event may have been within about 2 percent of the actual 1844 peak. It seems apparent that the peak discharge of the 1993 flood is the largest flow rate seen in the Middle Mississippi River Valley since before colonial settlers observed the first significant flood in 1785.

CONCLUSIONS

The main conclusions resulting from the series of tests and from the Great Flood of 1993 include

- Stage-frequency relationships for today's conditions are not greatly different from those for the 1820 time frame, when humans first began clearing the bankline and floodplain.
- The clearing and draining of the Middle Mississippi floodplain during the 1800s and early 1900s caused a significant decrease in stage for a given flood discharge.
- Federal levees alone result in a 0.1 to 1.2 m (0.3 to 4 ft) increase in flood heights for a given discharge in St. Louis compared with 1820 conditions, less than one-half the amount estimated by private groups and individuals in the past.
- Levees protecting the urban areas near St. Louis during the 1993 flood caused an increase of about 0.9 to 1.2 m (3 to 4 ft) in flood levels for several kilometers upstream. However, federal flood control reservoirs reduced flood levels at St. Louis by about the same amount, offsetting the adverse effects of levees on unprotected areas.
- Upstream flood control reservoirs fully offset the effects of federal levees for floods on the Middle Mississippi River in St. Louis.
- Structural flood control systems of levees, floodwalls, and reservoirs greatly reduced actual flood damages during the 1993 flood. An estimated $19 billion in damages was prevented by federal flood protection projects.
- If the meteorological and climatological events of 1993 had occurred in the early 1800s, the crest stages in St. Louis likely would have been similar to the actual stages of 1993.
- Published flood discharges along the Middle Mississippi before about 1930, after which time float measurements were no longer used, appear to be seriously overestimated. The key floods of 1844 and 1903 appear to be 33 and 23 percent overestimated. The 1973 flood may be the third highest discharge on record, after the 1844 event and the record 1993 flood.

SUMMARY

Although precise knowledge of the actual channel and floodplain conditions in 1820 will never be known, the series of tests performed for conditions as they were believed to exist in 1820, in 1940, and for today have shown far less negative effects of federal levees than had previously been estimated. The federal flood reduction program for the Mississippi River, which has been ongoing for over 50 years, has accomplished a great deal for areas protected by levees. Federal reservoirs, an important part of the flood reduction program, have offset the negative results on unprotected areas in the St. Louis area caused by federal levees. The stage-frequency relationships along the Middle Mississippi River are little different under today's conditions compared with the estimated conditions of 1820. The occurrence of the Great Flood of 1993 served to verify these earlier studies on federal levee effects near St. Louis and to demonstrate the value of the federal flood protection program.

An earlier version of this paper, with the same title, was written in December 1993 and was presented at the American Institute of Hydrology Convention in April 1994. This paper updates many of the statistics cited in the earlier version and includes additional and more accurate data from the 1993 flood than was available in December 1993. Therefore, this paper supersedes the earlier version.

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This paper represents the findings and opinions of the author and not necessarily those of the Corps of Engineers.