Technical Support Data Notebook

DFIRM Update for Fort Bend County, Texas, Part 2

Task 42 – Hydrologic Analyses
Brazos River

Prepared by

CF3R Joint Venture
Comprehensive Flood Risk Resources and Response

Riverine Flood Insurance Studies Through out FEMA Region VI

Contract No. EMT-2002-CO-0049
Task Order 022

January 2009

Baker Carter::Burgess MOFFATT & NICHOL ENGINEERS CDM

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I. Introduction

The Comprehensive Flood Risk Resources & Response Joint Venture (hereinafter referred to as CF3R) has completed the hydrologic analysis in accordance with Task Order 022, Task 42, for Fort Bend County, Texas. The hydrologic analysis completed for Task 42 were for the stream studied by detailed analysis only as stated in the contract task order. The hydrology consists of developing the peak discharges for the Brazos River for use in the hydraulic models. Data generated during the hydrology analyses was assembled and is included herein.

II. Project Work Statement (Task 42)

CF3R has completed the hydrologic analysis activities in accordance with Task Order 022, Task 42, for Fort Bend County, Texas. The Statement of Work for Task 42 is provided below:

Task 42 – Hydrologic Analyses

Responsible Entity: Contractor(s) selected for task order award.

Scope: Hydrologic analyses shall be completed for the drainage area of the flooding source(s) identified in the contract task order. The hydrologic methods used for this analysis shall be identified in the contract task order. Peak flood discharges shall be calculated based on the recurrence intervals identified in the contract task order for annual chance storms. These flood discharges shall be the basis for subsequent hydraulic analyses of the subject flooding sources. In addition, the Contractor shall address all concerns or questions regarding this task raised during the QASP review.

If GIS-based modeling is used, automated data processing and modeling algorithms shall be documented and provided to FEMA to ensure they are consistent with the standards outlined above. Digital data sets (such as elevation, basin, or land use data) shall be documented and provided to FEMA for approval prior to performing the analyses to ensure they meet minimum requirements. If non-commercial (i.e., custom-developed) software is used for the analysis, then full user documentation, technical algorithm documentation, and the software shall be provided to FEMA for review prior to performing the scope of work.

Task Order J022 Specific Task Scope (Brazos River)

- Gage Analysis will be conducted in order to determine the Brazos River Flow. It is expected that the flow hysteresis at the Richmond Gage would complicate the analysis effort
- Effect of Upstream Reservoirs will be analyzed based on existing reservoir records from the Brazos River Authority
- Flow distribution along the river will be determined based on analysis of adjacent drainage areas.
- Since the Brazos River affects major population centers in the County, flow determination methodology and results will be reviewed extensively by technical committees

Standards: All work conducted under this task shall conform to the standards specified for this task in Section 5, "Applicable Standards" of this SOW. In the event of any contradictions between the SOW and the standards, the standards shall control.

Deliverables: Upon completion of the hydrologic analyses, the Study Contractor shall submit a TSDN report document in the Region VI hydrology submittal outline format with required digital files delivered via CD or DVD. Additionally, the digital data shall either be uploaded to the MIP or developed on the MIP.

The Region VI hydrology submittal outline was developed in accordance with the Technical Support Data Notebook (TSDN) format described in Appendix M of *Guidelines and Specifications for Flood Hazard Mapping Partners*. At a minimum the submittal shall include, but is not limited to:

- Digital copies of all hydrologic modeling (input and output) files for specified recurrence intervals.
- "Summary of Discharge" Table(s) for each flooding source.

- Appropriate Contractor application/certification form for hydrology.
- All backup or supplemental information used in the analysis shall be provided for the government QASP.
- If GIS-based modeling is used, deliverables include all input and output data, intermediate data processing products, and GIS data layers.
- A QA/QC report that includes a description and the results of all automated or manual QA/QC steps taken during the Hydrologic Analyses. This report shall be certified in accordance with contractor's QAP Plan.
- NSP Format Hydrology Database or Intermediate Data Delivery consistent with the NSP Data Capture Standards and Guidelines.

The Data Capture Standards and Guidelines can be downloaded from http://www.fema.gov/fhm/dl_cgs.shtm.

III. Location and General Description

Fort Bend County is located in the southeastern portion of Texas, as shown in **Figure 1** below. It is bordered by Waller County to the north, Wharton County to the south and west, Harris County to the north and east, Brazoria County to the south and east, and Austin County to the west. The county is approximately 886 square miles in size and had a population of 419,772 people at the time of the 2003 census. Richmond is the county seat and is located in the central part of the county approximately twenty-eight miles west-southwest of Houston. Sugar Land, located in the northeastern region of the county, is the largest city.

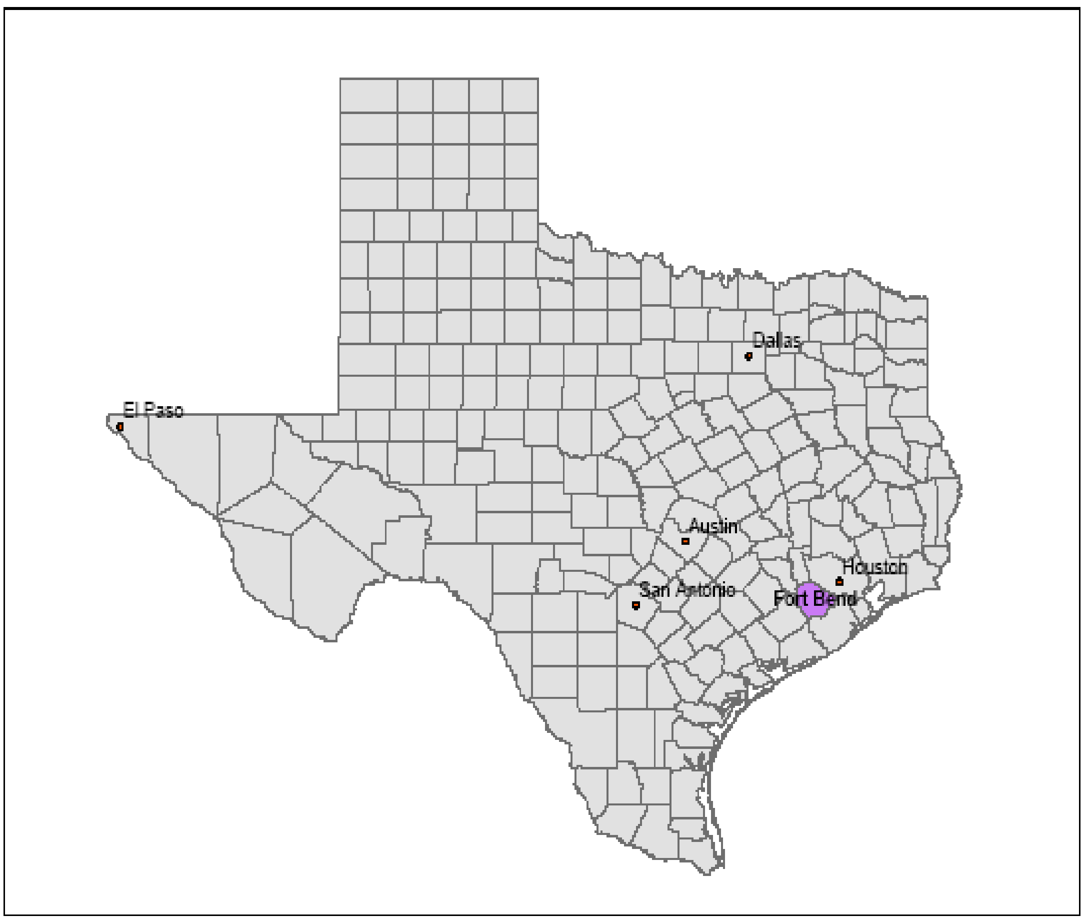

Figure 1: Fort Bend County, Texas

The **Brazos River** is the longest river in Texas at 1280 miles, beginning at Curry County, New Mexico and flowing 840 miles through the middle of Texas to the Gulf of Mexico. The Brazos River begins at the confluence of its Salt Fork and Double Mountain Fork near the eastern boundary of Stonewall County, Texas and runs 840 miles across Texas to its mouth on the Gulf of Mexico, two miles south of Freeport in Brazoria County and about 70 miles from Richmond in Fort Bend County. From the two Forks headwaters 150 miles above the confluence, the Brazos River watershed is 1,050 miles long, extending from New Mexico to the Gulf of Mexico and covering 44,620 square miles, 42,000 of which are in Texas (Reference 1).

Approximately 90 miles of the Brazos River run through Fort Bend County from northwest to southeast as shown in **Figure 2** below.

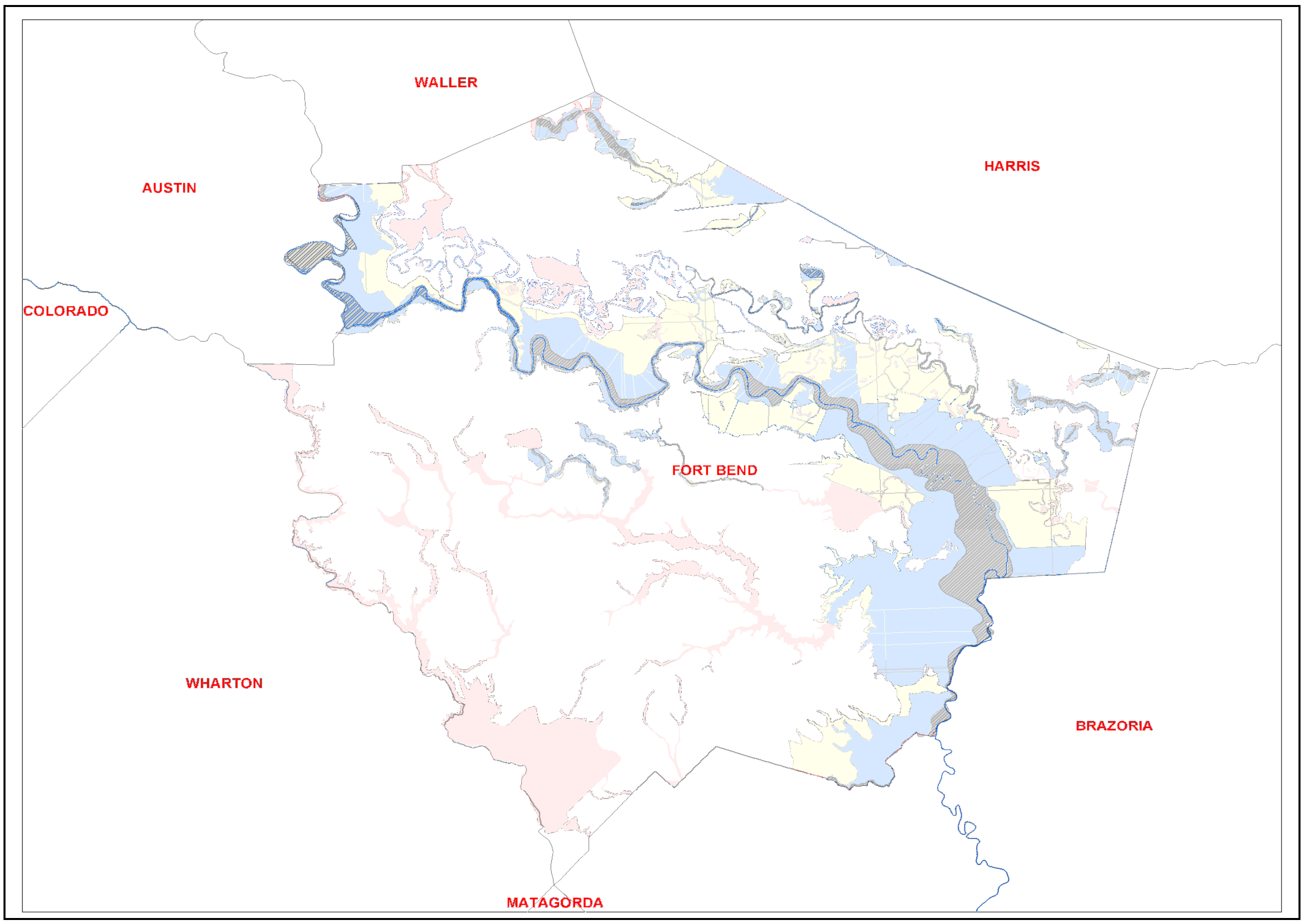

Figure 2: Brazos River and Its Effective Floodplain

Throughout its history, the Brazos River has experienced major flooding events. The first recorded major flooding occurs in 1833 as the water leaves the Brazos River's banks from Washington to Ringold's Prairie (near present-day Navasota). The latest severe flooding happened in 1913 as the Brazos River and the Colorado River joined to flood more than 3,000 square miles of land and caused the death of at least 177 people and massive property damage (Reference 2). The Brazos River Authority was established in 1929. It has statutory responsibility for developing and conserving the surface water resources of the Brazos River basin in Texas. The Authority in the early 1930s developed its first master plan for control, conservation, and development of the surface-water resources of the Brazos basin. The first major reservoir, Possum Kingdom Lake, was completed in 1941 on the main stem of the Brazos River northwest of Fort Worth. Eleven additional major reservoirs were completed since then, with the latest one, Aquilla Lake, completed in 1983 (Reference 1). **Figure 3** shows locations of reservoirs in the Brazos River Watershed

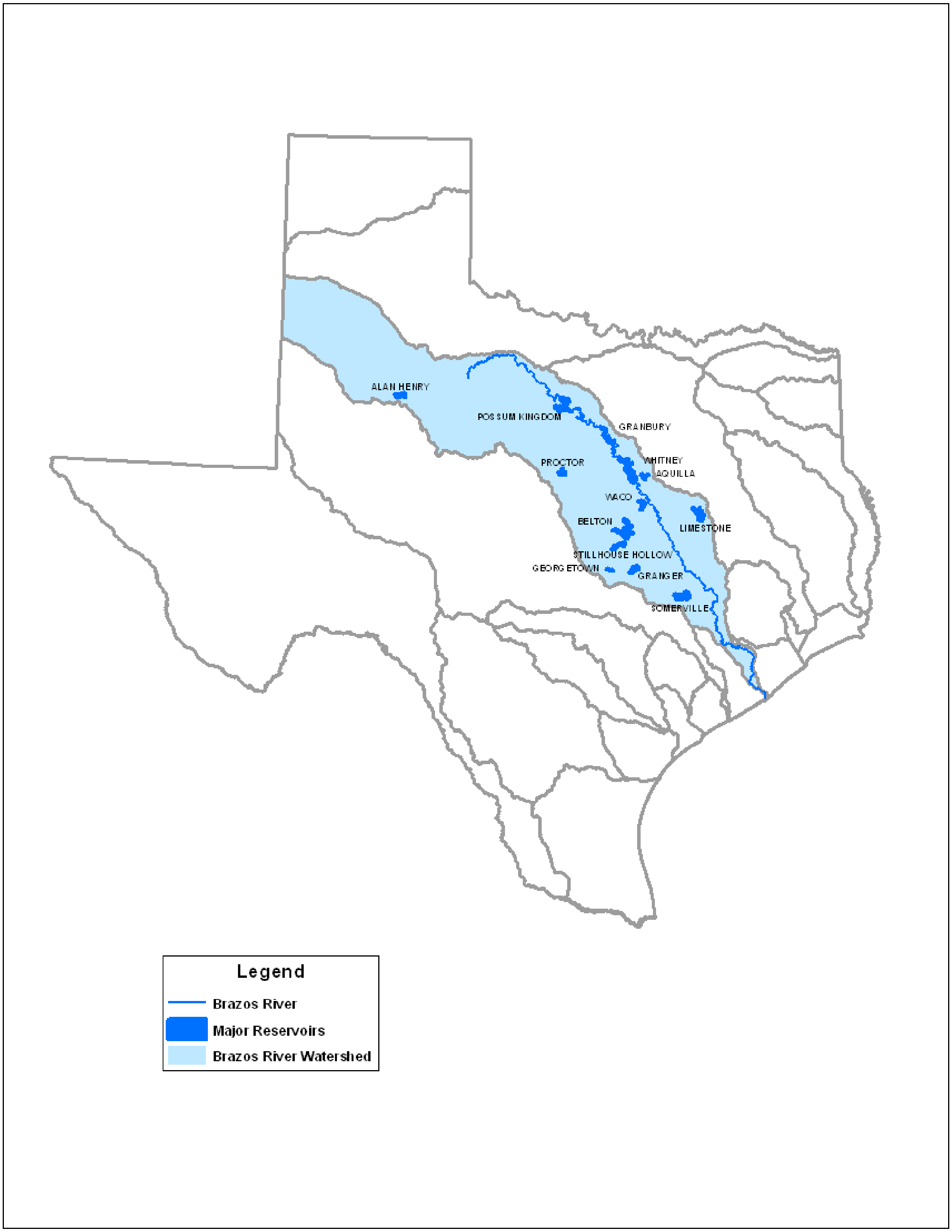

Figure 3: Brazos River and Its Effective Floodplain

IV. Previous Studies

i. 1977 Study by the USACE

In February 1977, a report prepared by USACE for the Fort Bend County Commissioners Court established the 1% peak flow for the Brazos River at Richmond to be 210,000 cfs (Reference 4).

ii. 1984 Flood Insurance Study by Espey Huston & Associates, Inc.

The initial countywide hydrologic and hydraulics analyses for Fort Bend County were completed by Espey Huston & Associates (EHA) for FEMA in May 1984. EHA developed a methodology to reanalyze the Brazos River gage data at Richmond (Reference 3). This methodology was used due to the special problems presented by progressive development of major flood control structures within the Brazos River basin. The staged development of dams and reservoirs caused non-homogeneity in gage records between 1941 and 1982; therefore, the direct application of the log-Pearson Type III distribution would have given erroneous results. Recorded flows were adjusted to "unregulated flow conditions by adding the net change in reservoir storage". The HEC-1 computer program was utilized to produce "unregulated" flood flows to be used to the Flood Frequency with Pearson Type III. Once satisfactory calibration had been obtained without the reservoirs, the effect of the reservoirs was incorporated and a value for each flood flow was determined. Based on the EHA study, the 1% peak flow of the Brazos River at Richmond was reduced from 210,000 cfs to 181,000 cfs and was applied throughout the 90 miles of the River within Fort Bend County.

The original countywide Fort Bend FIS was printed in 1992. Since then, three revisions of the FIS report were made in 1997, 2000, and 2001 with revised floodplain mapping due to new levees along the River. There was no change in the Brazos River flow in those revised FIS reports. Major floods on the Brazos River in December1991, October 1994, and October 1998 produced concern that the 1% storm event used for the effective Flood Insurance Study of Fort Bend County was not correct. During the December 1991 storm event, the recorded stage at Richmond was about three feet above the rating curve that was used to establish the effective FIS flows. Subsequent flooding events in October 1994, and October 1998 confirmed that shift. Due to this issue and the fact that there is an additional 20 years of data since the EHA study, an updated flood frequency analysis is necessary.

V. Methodology

For this study, CF3R has contracted LJA Engineering & Surveying, Inc. (LJA) to perform the flood frequency analysis of the USGS Gage at Richmond. Analysis of the flow attenuation along the Brazos River was performed by CF3R.

i. Flood Frequency Analysis of the Richmond Gage Data

The methodologies used for the hydrologic analyses performed for this study closely followed recommendations set forth in the Bulletin 17B "Guidelines for Determining Flood Flow Frequency" published by the United States Water Resources Council in 1981 to use the Pearson Type III distribution as a base method to determining flood flow frequency. Frequency Analysis assumes a stationary data sequence. Construction of the reservoirs has introduced non-stationary data. Bulletin 17-B does not provide guidance when watershed changes have affected the magnitude, homogeneity, or randomness of measured peak discharges. LJA developed a methodology to adjust recorded (regulated) discharge data to a uniform (unregulated) watershed condition. The approach is explained in detail in Appendix B-1.

The annual peak discharge data from the USGS Gage at Richmond (Station 0811400) from 1923 to 2004 together with selected historic flood data were utilized as the main component of the flood frequency analysis. Based on the reservoir data, the total runoff volume for each event was estimated and relationship was developed between the "regulated" and "unregulated" flows. Curves developed for the adjustment are shown on **Figure 4**.

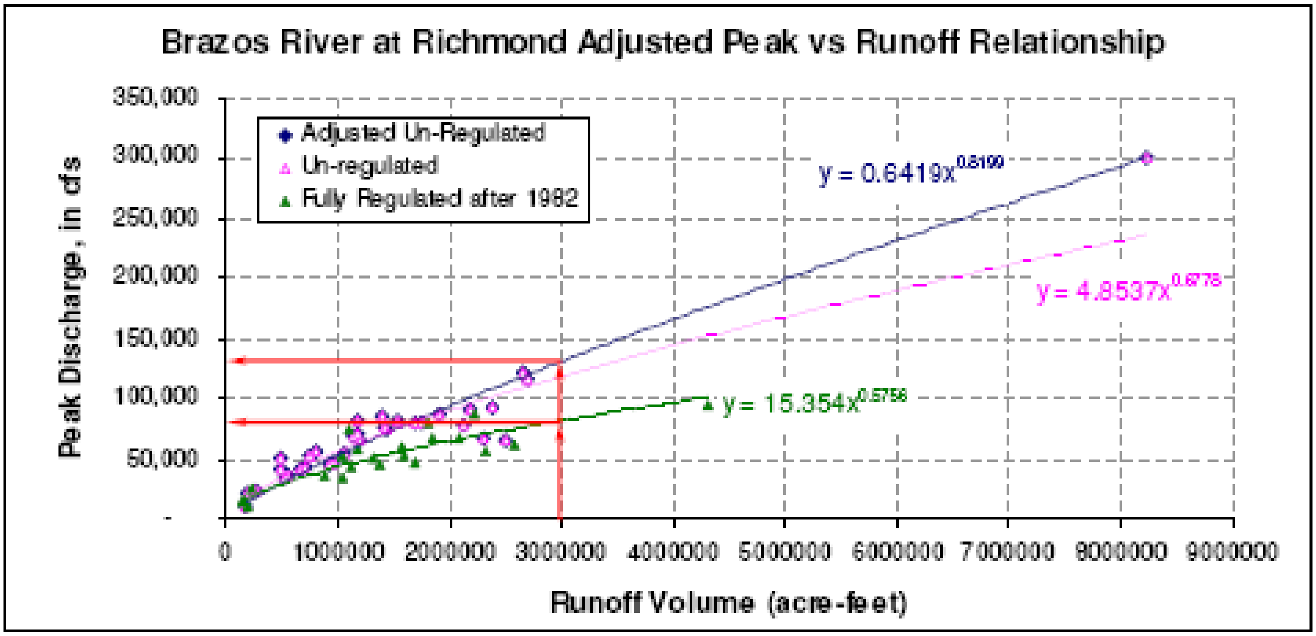

Figure 4: Regulated and Unregulated Flow Relationship

Once the recorded flows were converted to "unregulated" flows, flood frequency analysis for the unregulated flows can be applied to determine "unregulated" flows for different return intervals. The conversion factors developed earlier can then be used to convert the "unregulated" flows into "fully regulated" conditions. **Table 1** shows the proposed peak flows of various storm events for the Brazos River at Richmond.

TABLE 1: PROPOSED PEAK FLOWS OF BRAZOS RIVER AT RICHMOND

Probability	Return Interval (year)	Unregulated Flows (cfs)	Regulated Flows (cfs)
0.1	10	134,000	103,000
0.02	50	192,000	147,000
0.01	100	215,000	164,000
0.002	500	246,000	202,000

ii. Flow Attenuation

The EHA 1984 study has assumed the 100-year flow computed at Richmond stay unchanged for the entire 90 miles of river within Fort Bend County. Due to this long distance, some attenuation of the peak flow should occur. For this study, CF3R performed an analysis of the flow attenuation for the Brazos River between the Hempstead, Richmond, and Rosharon USGS gauging stations (see **Figure 5** for locations of those stations). The analysis compared the annual peak flow data between the 3 gauging stations for the period of 1939 to 2004. The analysis determined that the peak flows are reduced about 10% to 20% from Hempstead to Richmond and about 10 % from Richmond to Rosharon. Details of the analysis are provided in the **Flow Attenuation Memorandum** dated July 2008 shown in **Appendix B-2**.

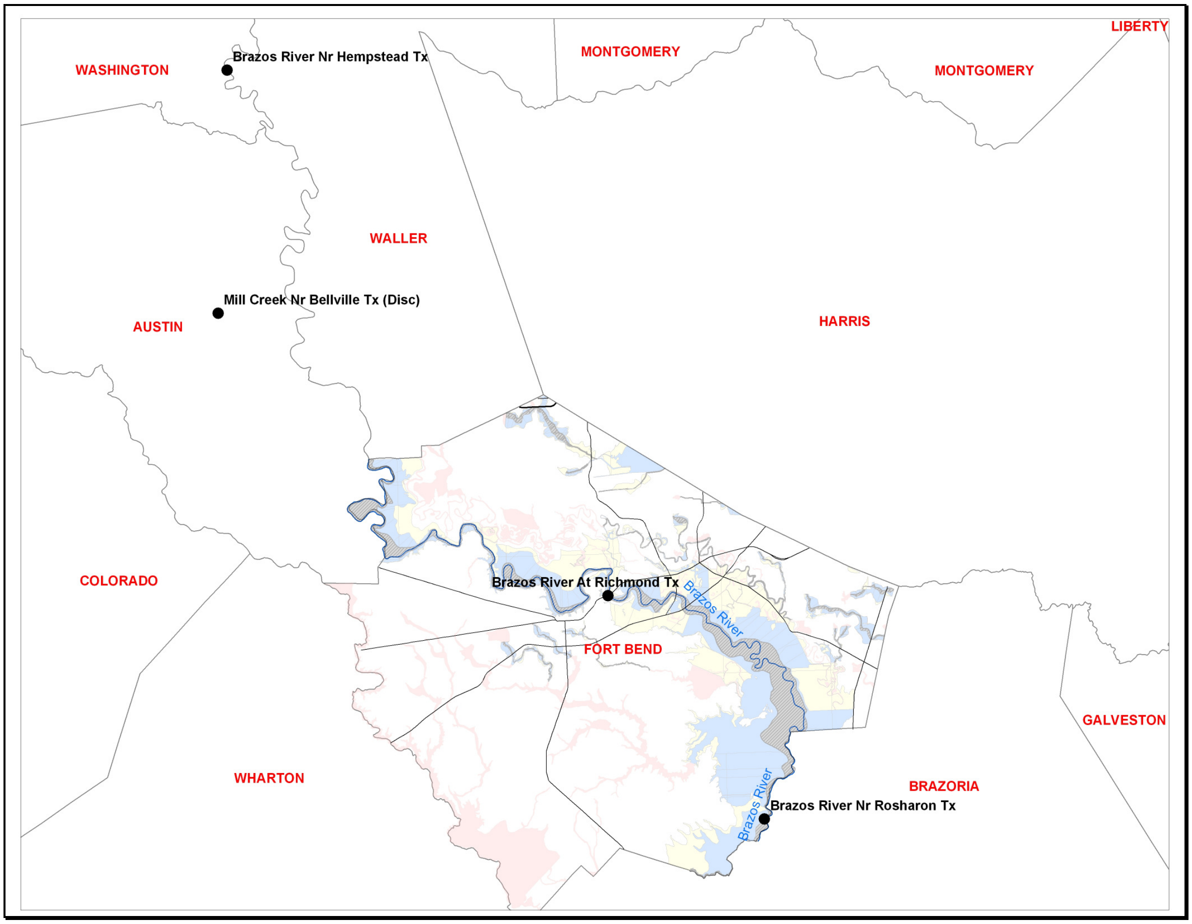

Figure 5: Locations of USGS Gaging Stations

The unsteady flow option of HEC-RAS was used as the main tool to calculate the flow distributions of different flow events from the Waller/Fort Bend County line to Brazoria/Fort Bend County line. The percentages of flow reduction between the Waller/Fort Bend County line and Richmond Gage are shown on **Table 2**.

TABLE 2: Flow Reduction Percentage from Waller/Fort Bend County Line to Richmond Gage

Location	Storm Event	Flows (cfs)	Peak Flow Reduction Percentage at US 90A
Waller/Fort Bend County	91	96,200	
Richmond Gage (US 90A)	91	94,000	2.34 %
Waller/Fort Bend County	1%	171,700	
Richmond Gage (US 90A)	1%	164,000	4.70 %

The unsteady HEC-RAS results showed that most of the attenuation from Hempstead Gage to Richmond Gage would occur in Waller County. The results were validated by the evaluation of the topography and the effective Brazos River floodplain in Waller County and Fort Bend County (see **Figure 6**). The proposed flow distribution of 1991 and 1% storm event from Waller/Fort Bend County Line to Richmond Gage (US 90A) are shown on **Table 3**.

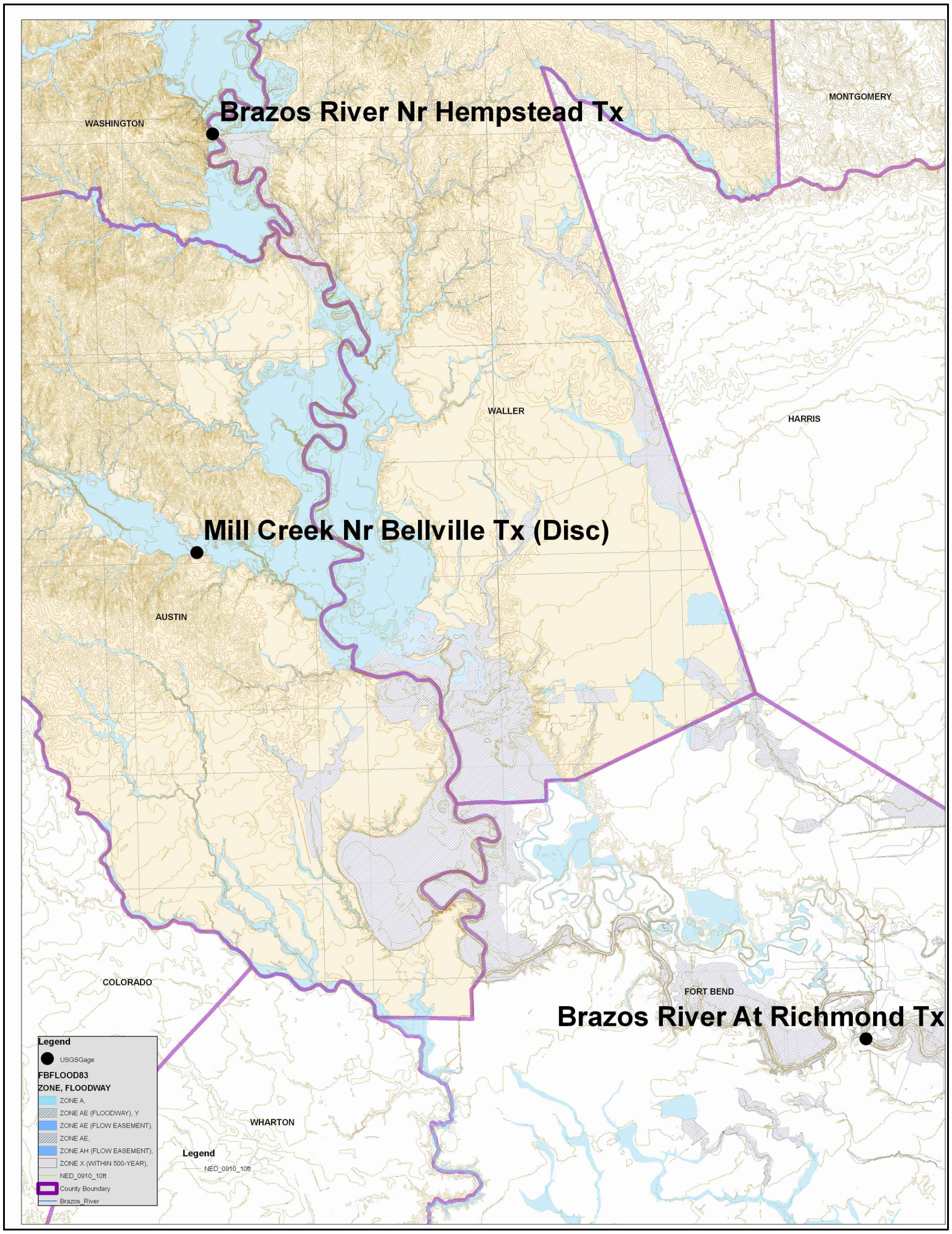

Figure 6: Effective Floodplain between Hempstead and Richmond USGS Gages

Table 3: Proposed Flow Distribution in 1991 and 1% Storm Event

Location	HEC-RAS Station (ft)	Dec 1991 event	1% Flood Event
Waller/Fort Bend County	468115	96,200 cfs	171,700cfs
Upstream of FM 1093	417909	94,800 cfs	168,000 cfs
Upstream of FM 723	302479	94,400 cfs	165,700 cfs
Richmond USGS Gage	208514	94,000 cfs	164,000 cfs
Brazoria/Fort Bend County	62793	94,000 cfs	162,000 cfs

a. Tie-in Conditions at Brazoria and Waller Counties:

As shown on **Figure 3**, approximately 10 miles of the Brazos River from the confluence with Cow Creek to downstream of FM 1093 are parts of the county line between Fort Bend and Brazoria County. In 1986, the U.S. Army Corps of Engineers (USACE) study for the Brazoria County FIS determined that due to a lower topography to the east, high flows from the Brazos River along the Fort Bend / Brazoria County line overflowed in an easterly direction. Due to the overflow, the 1% flow of Brazos River (in the effective Brazoria FIS report) is reduced from 181,000 cfs at Brazoria/Fort Bend County line to 103,189 cfs at the confluence of Brazos River with Cow Creek. Based on the flow distribution of the effective Brazos River HEC-2 model from the Brazoria County, the 1% flow distribution for the Brazos River HEC-RAS model was adjusted to reflect the gradual flow drop from 162,000 cfs at the Brazoria/Fort Bend County line (Station 62793) to 103,189 cfs at the confluence of Cow Creek and Brazos River (Station 431).

VI. Exceptions

There were no deviations from the Performance Work Statement or FEMA's Guidelines and Specifications.

VII. Results and Conclusions

The proposed Brazos River flows from the Gage Analysis at Richmond Gage are lower than the effective flows, except for the 10% event. The comparisons of the peak discharges at Richmond for various flood events between the 2001 Fort Bend FIS study and this study are shown on **Table 4**.

TABLE 4: PEAK FLOW COMPARISONS AT RICHMOND GAGE					
LOCATION	Study	10 %	2%	1%	0.2%
Richmond Gage	CF3R	103,000	147,000	164,000	202,000
	2001 FIS	101,000	157,000	181,000	242,000

Table 5 shows the flow distribution along the Brazos River within Fort Bend County.

TABLE 5: FLOW DISTRIBUTION FOR BRAZOS RIVER

Location	HEC-RAS Station (ft)	10% Flow	2% Flow	1% Flow	0.2% Flow
Waller/Fort Bend County	468115	105400	153900	17170	211500
Upstream of FM 1093	417909	103900	150600	168000	206900
Upstream of FM 723	302479	103400	148500	165700	204100
Richmond USGS Gage	208514	103000	147000	164000	202000
Brazoria/Fort Bend County Line	62793	103000	145000	162000	200000
	54416	103000	143000	160000	198000
	48774	103000	140844	155643	192430
	41067	103000	133570	145769	176356
	36123	103000	124521	133487	164898
	29208	103000	114541	119939	134357
	25409	103000	108000	112000	124000
	21940	103000	105100	108200	116000
	17870	103000	104524	107380	114464
	13523	103000	103328	105676	111275
	10664	96100	102545	104561	109187
	8169	96100	102487	104475	109031
	2630	96100	101722	103500	107200
Cow Creek and Brazos River	431	96100	101722	103189	106591

VIII. References

1. Texas State Historical Association, The Handbook of Texas Online, www.tsha.utexas.edu/handbook/online/ assessed February 2007.
2. Brazos River Authority Website, www.Brazos.org, Timeline of the Brazos River basin
3. Espey, Huston & Associates, Inc., Reassessment of 100-year Peak Flow, Brazos River at Richmond, Austin, Texas, May 1984
4. Espey, Huston & Associates, Inc., Brazos River Hydraulic Analysis, Fort Bend County, Texas, Houston, Texas, December 1985.
5. Federal Emergency Management Agency, Flood Insurance Study, Fort Bend County and Incorporated Areas, Texas, revised November 7, 2001.
6. Federal Emergency Management Agency, Flood Insurance Study, Waller County Unincorporated Areas, Texas, revised May 4, 1988.
7. Federal Emergency Management Agency, Flood Insurance Study, Brazoria County and Incorporated Areas, Texas, revised September 22, 1999.

APPENDIX B

BRAZOS RIVER WITHIN FORT BEND COUNTY, TEXAS

FLOOD FREQUENCY ANALYSIS

LJA Engineering & Surveying, Inc.

October 2006

BRAZOS RIVER PEAK FLOW ANALYSIS, July 2008

BRAZOS RIVER
WITHIN FORT BEND COUNTY, TEXAS

FLOOD FREQUENCY ANALYSIS

STATE OF TEXAS
CAROLYN SUE GILLIGAN
60852
REGISTERED
PROFESSIONAL ENGINEER

Prepared for
Michael Baker Jr. Inc.
Fort Bend County Drainage District
Federal Emergency Management Agency

October 2006

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LJA Job Number 1060-0501

PREFACE

This report is the result of a ten-month study effort to provide an assessment of the flood frequency relationship for the Brazos River at Richmond, Texas. The goal of the study was to achieve an updated estimation of the flood frequency relationship by extending the work done previously for the 1987 Fort Bend County, Texas Flood Insurance Study. The report's findings are based on a review of relevant technical literature, extensive flood frequency analyses and discussions by the technical review committee.

The technical review committee appointed by the Fort Bend County Drainage District (FBCDD) consisted of five Professional Engineers with expertise in hydrologic engineering. The committee incorporated input, when appropriate, from FBCDD personnel and experts from Michael Baker Jr, Inc. (Baker), the Federal Emergency Management Agency (FEMA) contractor updating Flood Insurance Rate Maps (FIRM's) for Fort Bend County, Texas. The following individuals were involved with the review process as members of the technical review committee:

Alejandro C. Flores, P.E., C.F.M. – Dannenbaum Engineering Corporation, Inc.
Gary L. Struzick, P.E., C.F.M. – Klotz Associates
Lawrence G. Dunbar, P.E.
Lee C. Lennard, P.E. – Brown & Gay Engineers, Inc.
Stephen C. Costello, P.E. – Costello, Inc.

Other individuals involved with the review include the following:

Andrew Cao, Ph. D., C.F.M. – Baker
Dong Nguyen, P.E., C.F.M. – Baker
Wilbert O. Thomas, Jr., - Baker Civil, Alexandria, Virginia
Mark Vogler, P.E. – FBCDD
Juling Bao, P.E. – FBCDD
Steven L. Johnson, P.E. – LJA Engineering & Surveying, Inc.

The first Section of this report provides a brief overview of the historical and on-going flood protection measures on the Brazos River, associated technical issues and the procedures used to develop the flood frequency relationship that was used for the effective Brazos River Flood Insurance Study (FIS). Section 2 provides a description of the data types that can be used to estimate flood exceedance probabilities for the Brazos River and discusses the available historical data. Section 3 discusses the recommended technique for flood frequency analysis based on fitting a Pearson type III analysis to the base 10 logarithms of the peak discharges, as described in Bulletin 17B, "Guidelines for Determining Flood Flow Frequency" published by the United States Water Resources Council in 1981. Section 4 details the method used to convert peak discharges recorded after construction of the upstream reservoirs to unregulated peaks, in order to obtain a homogeneous data set for use in the flood frequency analysis. Section 5 presents the updated flood frequency analysis for the Brazos River at Richmond, Texas that validates the method used previously for the effective FIS and updates the flood frequency relationship based on additional recorded discharges, using station skew and incorporating a historical period of record.

The report has been reviewed by individuals chosen for their technical expertise. The reason for the independent technical review was to 1) provide critical technical review of the process used to adjust the recorded discharges to obtain a homogenous data set, 2) evaluate the options presented for the flood frequency analysis and 3) select the appropriate flood frequency curve for use in the updated FIS for Fort Bend County, Texas.

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EXECUTIVE SUMMARY

Effective planning and design of flood risk management and flood protection projects require accurate estimates of flood risk. The purpose of this study was to achieve an updated estimation of flood frequency relationships for the Brazos River considering the changes that have occurred in the watershed since the original Flood Insurance Study was completed in 1987 and to establish a viable method by which the flood frequency relationships can be updated in the future. The availability of almost 20 years of additional flow data from the USGS stream flow gage at Richmond since the original Flood Insurance Study (FIS) was completed in 1987 will affect the flood frequency relationship. The findings are based on review of the previous flood frequency analysis, extensive revised flood frequency analysis and discussions with the FEMA technical consultant, the Fort Bend County Drainage District and other stakeholders.

The Brazos River basin has the largest drainage area of all basins between the Red River and the Rio Grande River in Texas, encompassing all, or part of 70 counties. Through history, the Brazos River and its tributaries have been subject to severe, destructive flooding. In 1913, the Guadalupe and Trinity Rivers left their banks, joining the Colorado and Brazos River to cover more than 3000 square miles of land and cause the deaths of at least 177 people and massive property damage and causing the river to change course. This event and another severe flood in 1921 were the catalyst for creation of the Brazos River Conservation and Reclamation District (renamed the Brazos River Authority in 1955) to "conserve, control and utilized to beneficial service the storm and flood waters of the Brazos River and its tributary streams".

The BRA developed its first master plan for control, conservation and development of the surface-water resources of the Brazos River basin in 1930, which proposed construction of 13 major dams on the Brazos River and its tributaries. In the 1940's, the BRA began working closely with the USACE and contracted with the federal government for inclusion of conservation storage space in nine reservoirs throughout the Brazos River basin. These reservoirs, Lakes Aquilla, Belton, Georgetown, Proctor, Somerville, Stillhouse Hollow, Waco and Whitney, are integrated into the BRA's basin-wide system of reservoirs in accordance with its master plan for water resource development.

The most important data set used for the flood frequency analysis of the Brazos River at Richmond is the annual peak discharge data compiled by the USGS (Station 08114000 with a drainage area of approximately 45,007square miles, of which 9,566 square miles is probably noncontributing). In Fort Bend County, the Richmond gage has been active intermittently since January 1903 and consistently since October 1922. All of the discharges recorded at the Richmond gage since about 1940 have been affected by the upstream reservoirs, therefore, although approximately 87-years of flow records are available for the Brazos River in Fort Bend County, Texas, the procedures for estimating flood frequencies in the lower Brazos River basin are complicated due to the construction of the major flood-control reservoirs throughout the basin between 1951 and 1980.

Major floods on the Brazos River in December 1991 to January 1992 and in October 1994 raised concern that the 1-percent annual chance flood flow used for the FIS for Fort Bend County, Texas was inaccurate. The computer models establishing the base flood elevations (BFE's) for the FIS were calibrated using the historic discharge and stage data from the "rating curve" for the Richmond gage. A rating curve, which defines the relationship between stage and discharge at a specific location in a stream, is derived by measuring the velocity of the current at various water levels, computing the discharge based on the cross-section of the channel at the gage location and constructing a curve that best fits the accumulated discharges. A review of the rating curves for the Richmond gage showed that stage-discharge relationship has moved continually, starting to drop in the 1920's and 1930' to a low point (lowest flood level for a given flow) in 1965. The curve then began to rise. USGS stream flow measurements showed the 1992 flood level was about three feet above the 1957 rating curve; the stream flow measurements for the 1994 flood showed an additional increase of two additional feet. In other words, using the discharge established for the 1994 flood in the FIS computer model of the Brazos River would result in a water surface elevation at the gage location about five feet below the observed stage.

Bulletin 17B, "Guidelines for Determining Flood Flow Frequency" published by the United States Water Resources Council in 1981, recommends using the Pearson Type III distribution with log transformation of the data (log-Pearson Type III distribution) as a base method for determining flood flow frequency. Bulletin 17B also provides procedures for weighting a station skew value with the results from a generalized skew study, detecting and treating outliers, making two station comparisons, and computing confidence limits about a frequency curve. Frequency analysis assumes a stationary data sequence. Construction of the flood-control reservoirs has introduced non-stationary data. Annual maximum discharge estimates using the pre-reservoir data, or analysis of the non-stationary data would, therefore, not be accurate estimates of the annual maximum discharge that would occur under the current watershed conditions. Bulletin 17B does not provide guidance for flood frequency analysis when watershed changes have affected the magnitude, homogeneity, or randomness of measured annual peak discharges. It was, therefore, necessary to develop a method to adjust recorded discharge data to a uniform (unregulated) watershed condition.

Changes made by the United States Water Resources Council in the methods used to determine flood flow frequency and changes in the estimates of historical flood flows in the Brazos River precipitated a reassessment of the 1-percent annual chance discharge at the Richmond gage when the Fort Bend County FIS was being prepared by Espy, Huston & Associates, Inc. (EHA) in the early 1980's. The recommended 1-percent annual chance discharge resulting from the reassessment was 181,000 cfs. .

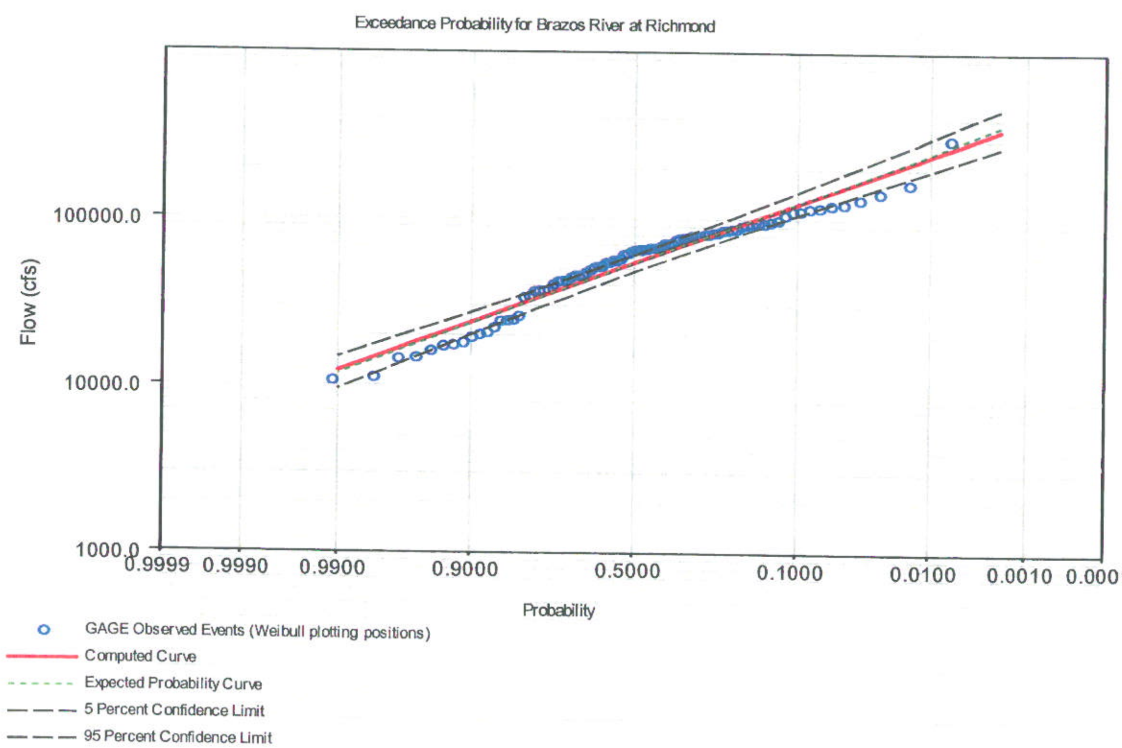
The procedure used by EHA to estimate the flood frequencies for the Brazos River FIS used the following steps:

1. Estimate the unregulated annual peak flows from gage records for years subsequent to reservoir construction by routing daily changes of reservoir storage to the Richmond gage and adjusting the recorded peak discharge by adding the net change in storage.
2. Compute the flood frequency curve as recommended in Bulletin 17B

3. Develop a HEC-1 computer model of the Brazos River watershed that results in the unregulated frequency estimates.
4. Use the "calibrated" HEC-1 model to route the unregulated hydrographs through the reservoirs existing in 1984 to obtain the regulated frequency curve.

A historical flood is a major flood that occurred outside the period of systematic stream gaging. The stage or elevation of the historical flood is usually determined by high water marks left by the flood that were recorded for posterity. Because the historical event was not observed according to definite statistical sampling criteria, and is not part of the systematic record, its relation to the underlying process of flood occurrence is uncertain. This is so regardless of the accuracy with which the stage and discharge might have been determined. The historical flood cannot be used in flood frequency analysis unless additional information (historical threshold and historical period) is available to relate it to flood occurrence over a historical time period. Bulletin17B considers information indicating that any flood peaks that occurred before, during, or after the systematic record are maximums in an extended period of time data that should be used in frequency computations.

The flood frequency analysis for the FIS used historical data from the 1884, 1885, 1899, 1913 and 1915 floods, after adjusting the assumed peak discharges for the 1884 and 1885 events. No historic period of record was used in their flood frequency analysis. The resulting flood frequency curve is shown below.



The 1-percent annual chance discharge was determined to be approximately 238,000 cfs. The results of the HEC-1 model routing the Brazos River discharge through the reservoirs indicated a regulated 1-percent annual chance discharge at the Richmond gage of 181,000 cfs, which was used for the Fort Bend County FIS.

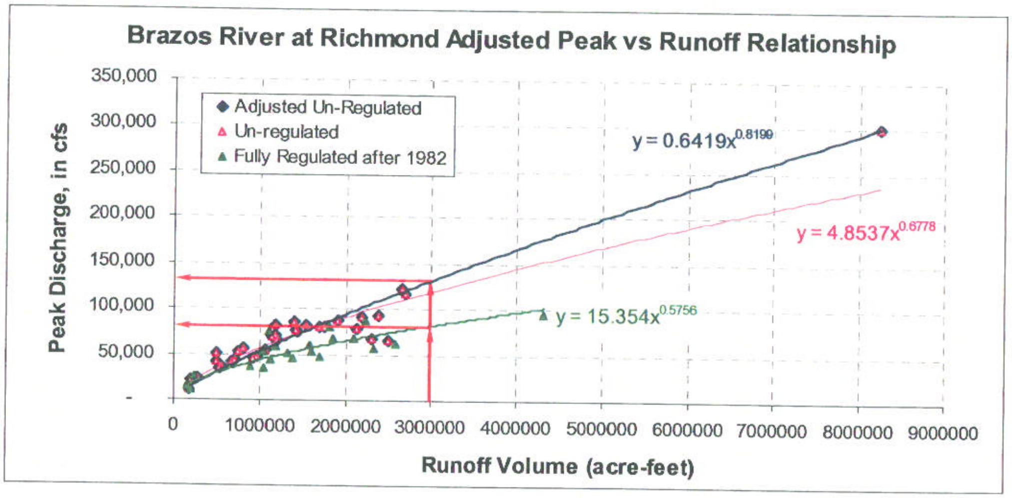
For this update to the FIS, the following, simple, method was used to determine a conversion from regulated to un-regulated conditions for the annual peak discharges recorded at the Richmond gage:

- using USGS daily peak flow water data create flow hydrographs for each water year and determine the runoff volume for each annual peak discharge
- determine the reservoir storage volume for each peak event
- combine the runoff volume and storage volume to determine the total runoff volume for the event.
- plot the relationship of total volume versus recorded annual peak flow for the regulated, partially regulated and fully regulated periods.
- develop mathematical equation for the three runoff volume versus peak flow relationships, forcing the equation for the unregulated period through the 1913 flood
- using the equations developed for the unregulated and fully regulated periods, compute the theoretical annual peak flows for the unregulated and fully regulated conditions for the partially and fully regulated period
- using the ratio of the unregulated to regulated theoretical peak flow, adjust the measured flow to unregulated conditions
- further adjust the annual peak flow for the partially regulated period using the percentage of reservoir volume in place at the time of the peak event.

The systematic data was divided into three segments to reflect pre- and post-reservoir data, as follows:

- Unregulated discharge – 1903 to 1952
- Partially regulated discharge – 1952 to 1982
- Regulated discharge – 1983 to 2004

Trend lines were computed for the unregulated and regulated data sets, and the theoretical annual peak discharges for regulated and unregulated conditions were then established as shown in the following chart.



The ratio between the two derived annual peak flows was used to adjust the regulated and partially regulated annual peaks to unregulated condition. If the derived conversion factor was less than 1.0, however, then the annual peak discharge was not adjusted.

After adjusting the recorded flows for partial and full regulation to reflected unregulated conditions, the following data sets were analyzed to 1) validate the previous FIS probability distribution developed by EHA, 2) establish updated probability distribution using an additional 22 years of gage data, and 3) devise a method of adjusting the regulated discharge to unregulated conditions that can continue to be used until sufficient gage data is available to provide a probability distribution for regulated conditions. All data sets incorporated the 1884, 1885, 1899, 1913 and 1915 floods as historical data.

Brazos River at Richmond
Flood Frequency Analysis Data Sets

	Description	Skew	Defining Period	Systematic Data
1	Data Used for Fort Bend County FIS	Weighted	N/A	1903-1906 1923-1982
2	Using Simplified Method to Adjust Regulated Data to Unregulated Condition	Weighted	N/A	1903-1906 1923-1982
3	Using Simplified Method to Adjust Regulated Data to Unregulated Condition	Station	N/A	1903-1982 1923-1982
4	Using Additional 22 Years of Gage Records	Station	1852	1903-1906 1923-2004

The results of theses alternative frequency analyses are shown below:

Brazos River at Richmond Unregulated Discharge Probability Distribution					
Probability	Return Interval	FIS (1)	With Simplified Adjustment (2)	With Simplified Adjustment and Station Skew (3)	Adding 22 Years of Gage Data (4)
0.9999	1	9,620	9,820	9,820	8,970
0.5	2	57,600	62,000	62,000	62,700
0.2	5	100,000	107,000	107,000	106,000
0.1	10	131,000	138,000	138,000	134,000
0.05	20	163,000	169,000	169,000	160,000
0.02	50	205,000	209,000	209,000	192,000
0.01	100	238,000	239,000	239,000	215,000
0.005	200	271,000	269,000	269,000	237,000
0.002	500	316,000	308,000	308,000	264,000

The results from the analysis replicating the EHA study using the unregulated discharges developed for the current analysis reasonably matched the results of the 1987 study. It was, therefore, concluded that the simplified method use to adjust measured discharges for the Brazos River at the Richmond gage followed closely with the procedure used to adjust the discharges for the 1987 FIS, and that the method was valid and can be used in the future as additional measured data is obtained.

As stated above, EHA then developed a rainfall-runoff model of the Brazos River basin using the United States Army Corps of Engineers (USACE) Hydrologic Engineering Center HEC-1 computer program. The model was calibrated to produce a peak flow at Richmond of 238,000 cfs, which agreed with the 100-year flow value derived from the frequency analysis of the unregulated flows. Computations that used the same rainfall data and the same unit hydrograph parameters and routed the flow through each of the eight reservoirs resulted in a peak 100-year flow of 181,000 cfs, which indicates that the reservoirs reduce the unregulated 100-year peak discharge at Richmond by approximately 24-percent.

Because the reservoirs operation has not changed, the percentage of reduction in discharge was judged to be the same as determined for the Fort Bend County FIS. Therefore, after the flood frequency curve for unregulated conditions at the Richmond gage was developed, the regulated flood frequency curve was determined using relationship between the regulated and unregulated discharges that was developed for the 1987 FIS. The unregulated and regulated discharges are shown in the following table.

Brazos River at Richmond Updated Probability Distribution						
Probability	Return Interval	FIS Unregulated	FIS Regulated	Ratio	Updated Unregulated	Updated Regulated[1]
0.1	10	131,000	101,000	0.771	134,000	103,000
0.02	50	205,000	157,000	0.766	192,000	147,000
0.01	100	238,000	181,000	0.761	215,000	164,000
0.002	500	316,000	242,000	0.766	264,000	202,000

[1] Adjusted using the same ratio as the effective FIS discharges.

1.0 INTRODUCTION

Effective planning and design of flood risk management and flood protection projects require accurate estimates of flood risk. The "Flood Map Modernization" is a multi-year Presidential initiative supported by Congress that is directed at improving and updating the Nation's flood hazard identification maps. As initially envisioned in 2003, the Flood Map Modernization was focused on creating a digital flood layer for all communities at risk of flooding. However, States and professional organizations have expressed a preference for the Federal Emergency Management Agency (FEMA) to focus on developing flood maps that meet new higher standards for mapping and for greater allocation of resources to those communities at greatest flood risk.

The new mapping standard, called the Floodplain Boundary Standard, requires matching the available floodplain boundary (from a paper map) to the best available topographic information and merging both into a digital format. This process results in a digital map with a floodplain boundary corrected for any discrepancies in the paper maps boundary due to insufficient topographic detail available when the paper map was created. The Floodplain Boundary Standard alleviates the concerns of map users that improperly drawn boundaries would be transferred to the digital maps.

In addition to providing digital maps, the Flood Map Modernization was designed to provide for engineering updates, which include the update or validation of existing flood data or the development of new flood data for stream miles or areas not previously studied. There are several reasons for mapping updates. The most fundamental is that the severity of flooding may change with time and the maps provide a "snapshot" of the estimated 1-percent annual chance flood at a single point in time. The following natural and man-made changes to a watershed can cause changes in flooding and floodplains.

- The addition of impervious surfaces such as pavement and rooftops and other forms of development can alter the drainage patterns and timing and volume of runoff to floodplains leading to size and extent of floodplains.
- The NFIP minimum standard of allowing development or filling in the flood fringe, outside of the floodway but within the 1-percent annual chance floodplain can raise flood elevations up to one foot.
- The original design standards used for flood control infrastructure may become invalid as the structure ages and deteriorates.
- The magnitude and extent of on-going floods changes the underlying statistics of hydrologic data used in the previous flood studies.
- Channel migration and erosion can cause changes in flood risk zones.
- Ground subsidence can result in a higher level of flooding than is depicted on the maps.

The Brazos River within Fort Bend County, Texas is a case in point. Although the National Flood Insurance Program (NFIP) was created in 1968 with the passage of the National Flood Insurance Act, Fort Bend County did not join the program until November 1987. Even at that time a great deal of the data used to develop the 1-percent annual chance floodplain for the Brazos River was from earlier studies, including cross-sections of the channel that were based on data obtained by the United States Army Corps of Engineers (USACE) in 1939.[1] The United States Geological Survey (USGS) stream flow gage on the Brazos River at Richmond, Texas provided data used to estimate the 1-percent annual chance flood discharge that defined the effective base flood elevations (BFE's). The floodplain was mapped using USGS 1:24000 quadrangle maps with five-foot contour intervals and a substantial part of the Brazos River basin within Fort Bend County is subject to ground subsidence, so the mapped elevations are no longer accurate. It was appropriate, therefore, to update the hydrology and hydraulics of the Brazos River in Fort Bend County as part of the County's re-mapping effort.

The purpose of this study was to achieve an updated estimation of flood frequency relationships for the Brazos River considering the changes that have occurred in the watershed since the original Flood Insurance Study was completed in 1987 and to establish a viable method by which the flood frequency relationships can be updated in the future. The availability of almost 20 years of additional flow data from the USGS stream flow gage at Richmond since the original Flood Insurance Study (FIS) was completed in 1987 will affect the flood frequency relationship. The findings are based on review of the previous flood frequency analysis, extensive revised flood frequency analysis and discussions with the FEMA technical consultant, the Fort Bend County Drainage District and other stakeholders.

This section of the report provides a brief overview of the historical and on-going development and flood control measures on the Brazos River, associated technical issues, and policy implications. Section 2 provides a description of the data types that can be used to estimate flood exceedance probabilities for the Brazos River. Section 3 presents and discusses this study's flood frequency estimates for the Brazos River. Section 4 review additional issues that affect the flood frequency. Section 5 summarizes the results of the flood frequency analysis and recommends a flood frequency curve for use with the current re-study and re-mapping of the Brazos River 1-percent annual chance floodplain.

1.1 Background

The Brazos River basin has the largest drainage area of all basins between the Red River and the Rio Grande River in Texas, encompassing all, or part of 70 counties. Total basin drainage area is approximately 45,575 square miles, of which approximately 43,000 square miles are in Texas; the remaining area is in New Mexico.

Rising from the confluence of the Double Mountain Fork and South Fork the Brazos River continues for approximately 840 miles through most of the physiographic regions of Texas. The basin terrain below the Cap Rock escarpment, near Palo Pinto County, is rolling and crossed by low escarpments. The river channels are deeply entrenched and confined in narrow valleys with steep side bluffs. The floodplains in this area are narrow. When the river reaches the Balcones escarpment, the topography changes first to gently rolling, then to an almost flat plain, with a channel slope of 0.7 feet per mile, down to the Gulf of Mexico. With the less rugged terrain, the stream valleys are wide and flat, with correspondingly wide, shallow floodplains. At USGS stream-

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[1] Flood Plain Information Brazos River Fort Bend County, Texas, prepared for Fort Bend County, Texas by the U.S. Army Corps of Engineers, Galveston District, Galveston, Texas, February 1977.

flow gaging station 08114000 Brazos River at Richmond, Texas (Richmond gage), the channel is approximately 300 feet wide.

1.2 Risk Reduction Efforts

Through history, the Brazos River and its tributaries have been subject to severe, destructive flooding. Early documentation of the first recorded flooding occurred in 1833 when the Brazos River left its banks from Washington to Ringold's Prairie (near present day Navasota).[2] Major flooding also occurred in 1842, when the river widened to six miles for an extended distance[2]. In 1913, the Guadalupe and Trinity Rivers left their banks, joining the Colorado and Brazos River to cover more than 3000 square miles of land and cause the deaths of at least 177 people and massive property damage and causing the river to change course. This event and another severe flood in 1921 were the catalyst for creation of the Brazos River Conservation and Reclamation District (renamed the Brazos River Authority in 1955) to "conserve, control and utilized to beneficial service the storm and flood waters of the Brazos River and its tributary streams". Established by the Texas legislature in 1929, the Brazos River Authority (BRA) was the first public agency in the United States created to conserve and develop the resources of a major river basin.

The BRA developed its first master plan for control, conservation and development of the surface-water resources of the Brazos River basin in 1930, which proposed construction of 13 major dams on the Brazos River and its tributaries. The BRA's first order of business was to build a massive power dam and reservoir on the main stem of the Brazos River approximately 80 miles northwest of Fort Worth. Possum Kingdom Lake, a 17,700-acre reservoir was completed in 1941. Two additional reservoirs constructed by the BRA, Lake Granbury and Lake Limestone, were completed in 1969 and 1978, respectively.

In the 1940's, the BRA began working closely with the USACE and contracted with the federal government for inclusion of conservation storage space in nine reservoirs throughout the Brazos River basin. These reservoirs, Lakes Aquilla, Belton, Georgetown, Proctor, Somerville, Stillhouse Hollow, Waco and Whitney, are integrated into the BRA's basin-wide system of reservoirs in accordance with its master plan for water resource development.[3] The USACE also operates Lake Granger on the San Gabriel River. Selected characteristics of these reservoirs, which contain 88 percent of the controlled storage in the Brazos River Basin, are shown in Table 1.1.

Table 1.1
Brazos River Basin
Reservoirs

Reservoir	Stream Impounded	Year of Initial Impoundment	Drainage Area (sq mi)	Storage Capacity[1] (ac-ft)		
				Conservation Pool	Flood Control	Total
Possum Kingdom	Brazos River	1941	23,596[2]	570,240	154,460	724,700
Whitney	Brazos River	1951	27,189[2]	627,100	1,372,400	1,999,500

[2] Brazos River Authority website, www.brazos.org, Timeline of the Brazos River Basin

[3] "BRAZOS RIVER AUTHORITY." The Handbook of Texas Online, a joint project of The General Libraries of the University of Texas at Austin and the Texas State Historical Association

Table 1.1
Brazos River Basin
Reservoirs

Reservoir	Stream Impounded	Year of Initial Impoundment	Drainage Area (sq mi)	Storage Capacity[1] (ac-ft)		
				Conservation Pool	Flood Control	Total
Belton	Leon River	1954	3,531	457,600	633,720	1,091,320
Proctor	Leon River	1963	1,259	59,400	314,800	374,200
Waco	Bosque River	1965	1,652	152,500	573,900	726,400
Somerville	Yequa Creek	1967	1,007	160,100	347,400	507,500
Stillhouse Hollow	Lampasas River	1968	1,313	235,700	394,700	630,400
Granbury	Brazos River	1969	25,679	153,490	87,150	240,640
Limestone	Navasota River	1978	675	225,400	92,700	318,100
Georgetown	San Gabriel River	1980	247	37,100	93,710	130,800
Granger	San Gabriel River	1980	709	65,500	178,700	244,200
Aquilla	Aquilla Creek	1983	252	52,400	93,600	146,00

[1] Texas Water Resources Institute, Texas A&M University, Technical Report 144, Wurbs, et al, 1988.
[2] Approximately 9,566 square miles is probably non-contributing

Updated reservoir data from USGS Water-Data Report TX-96-2 shows slightly different storage capacities for some of the reservoirs, as shown in Table 1.2.

Table 1.2
Brazos River Basin
USGS Data for Reservoirs

Reservoir	Stream Impounded	Year of Initial Impoundment	Drainage Area (sq mi)	Storage Capacity (ac-ft)		
				Conservation Pool[1]	Flood Control	Total[1]
Possum Kingdom	Brazos River	1941	23,596[2]	556,200	NA	NA
Belton	Leon River	1954	3,531	434,500	644,500	1,079,000
Proctor	Leon River	1963	1,259	55,590	314,810	370,400
Waco	Bosque River	1965	1,652	152,500	573,900	726,400
Somerville	Yequa Creek	1967	1,007	155,100	347,400	502,500
Stillhouse Hollow	Lampasas River	1968	1,313	226,100	394,600	620,700
Granbury	Brazos River	1969	25,679	153,490	87,150	240,640
Limestone	Navasota River	1978	675	215,800	102,300	318,100
Georgetown	San Gabriel River	1980	247	37,010	93,690	130,700
Granger	San Gabriel River	1980	730	54,280	178,620	232,900
Aquilla	Aquilla Creek	1983	255	45,960	93,640	139,600

[1] USGS Water-Data Report TX-96-2.
[2] Approximately 9,566 square miles is probably non-contributing

Other reservoirs within the Brazos River basin include Fort Phantom Hill, Hubbard Creek, Squaw Creek, and Lake Pat Cleburne, with storage capacities as shown in Table 1.3.

Table 1.3
Brazos River Basin
Additional Reservoirs

Reservoir	Stream Impounded	Year of Initial Impoundment	Drainage Area (sq mi)	Storage Capacity (ac-ft)		
				Conservation Pool	Flood Control	Total
Fort Phantom Hill	Elm Creek	1938	470			74,310[1]
Hubbard Creek	Hubbard Creek	1962	1,085	317,750[2]	198,050[2]	515,800[2]
Squaw Creek	Squaw Creek	1977	64	151,000[3]	27,100[3]	178,100[3]
Pat Cleburne	Nolan River	1964	100			25,600[3]

[1] "FORT PHANTOM HILL RESERVOIR." The Handbook of Texas Online, a joint project of The General Libraries of the University of Texas at Austin and the Texas State Historical Association
[2] Texas Water Resources Institute, Texas A&M University, Technical Report 144, Wurbs, et al, 1988.
[3] "LAKE PAT CLEBURNE" The Handbook of Texas Online, a joint project of The General Libraries of the University of Texas at Austin and the Texas State Historical Association

Other flood damage reduction measures that have occurred within Fort Bend County include a substantial number of levees that have been constructed within the Brazos River flood fringe. Known levees within Fort Bend County are shown in Table 1.4.

Table 1.4
Brazos River
Levees within Fort Bend County

Maintenance Entity	Development	Location (River Mile)
Fort Bend County Levee Improvement District (LID) No. 2	First Colony	80-84.8
First Colony LID	First Colony	78.8-81.6
First Colony LID 2	First Colony – The Commonwealth	80-81.2
Pecan Grove Municipal Utility District (MUD)	Pecan Grove	93.1-94.1
Palmer Plantation MUD's 1 and 2	Lake Olympia	74.8-78.8
Fort Bend County MUD 49	Lake Olympia	74.8-75.8
Sienna Plantation LID	Sienna Plantation	65.8-74.8
Fort Bend County LID 7	New Territory	83.9-87
Fort Bend County LID 10	Riverpark	85-87
Fort Bend County LID 11	Greatwood	83-84.2
Fort Bend County LID 14	Avalon	81.1-81.6
Fort Bend County LID 15	Riverstone	78.8-80.9
Fort Bend County LID 17	Telfair	81.6-83.9
Fort Bend County MUD 121	Riverpark West	87-88.5
	Colony Lakes	74.8-78.8

1.3 Technical Issues

Major floods on the Brazos River in December 1991 to January 1992 and in October 1994 precipitated concern that the 1-percent annual chance flood flow used for the FIS for Fort Bend County, Texas was inaccurate. The computer models establishing the BFE's for the FIS were calibrated using the historic discharge and stage data from the "rating curve" for the Richmond gage. A rating curve, which defines the relationship between stage and discharge at a specific location in a stream, is derived by measuring the velocity of the current at various water levels, computing the discharge based on the cross-section of the channel at the gage location and constructing a curve that best fits the accumulated discharges. The rating curves are updated regularly to reflect any changes that may have occurred in the channel.

A review of the rating curves for the Richmond gage showed that stage-discharge relationship has moved continually, starting to drop in the 1920's and 1930' to a low point (lowest flood level for a given flow) in 1965. The curve then began to rise. USGS stream flow measurements showed the 1992 flood level was about three feet above the 1957 rating curve; the stream flow measurements for the 1994 flood showed an additional increase of two additional feet. In other words, using the discharge established for the 1994 flood in the FIS computer model of the Brazos River would result in a water surface elevation at the gage location about five feet below the observed stage.

Many watershed changes can affect the magnitude and variability of annual peak discharges and can affect the validity of flood-frequency analysis. Bulletin 17B, "Guidelines for Determining Flood Flow Frequency" published by the United States Water Resources Council in 1981, recommends using the Pearson Type III distribution with log transformation of the data (log-Pearson Type III distribution) as a base method for determining flood flow frequency. Bulletin 17B also provides procedures for weighting a station skew value with the results from a generalized skew study, detecting and treating outliers, making two station comparisons, and computing confidence limits about a frequency curve. Bulletin 17B does not provide guidance for flood frequency analysis when watershed changes have affected the magnitude, homogeneity, or randomness of measured annual peak discharges.

Watershed changes can introduce an episodic (abrupt) change or a secular trend in a flood series. An episodic change occurs in a very short time period relative to the length of the flood record; the continual change in a flood record caused when a change in the watershed process occurs over a relatively long time period is referred to as a secular change. For a secular change, the individual events in the flood record reflect different stages of a gradual watershed change. The records should be adjusted to reflect a specific watershed state in order to account for the nonhomogeneous nature of the flood record.

The Richmond gage has been active intermittently since January 1903 and consistently since October 1922, although its information was published as "at Rosenberg" from October 1922 to September 1931. All of the discharges recorded at the Richmond gage since about 1940 have been affected by the upstream reservoirs, which have been constructed in the Brazos River basin since the early 1900's. In the 1986, 1,178 reservoirs in the Brazos River Basin were listed in the dam inventory maintained by the Texas Commission on Environmental Quality[4] (TCEQ), although

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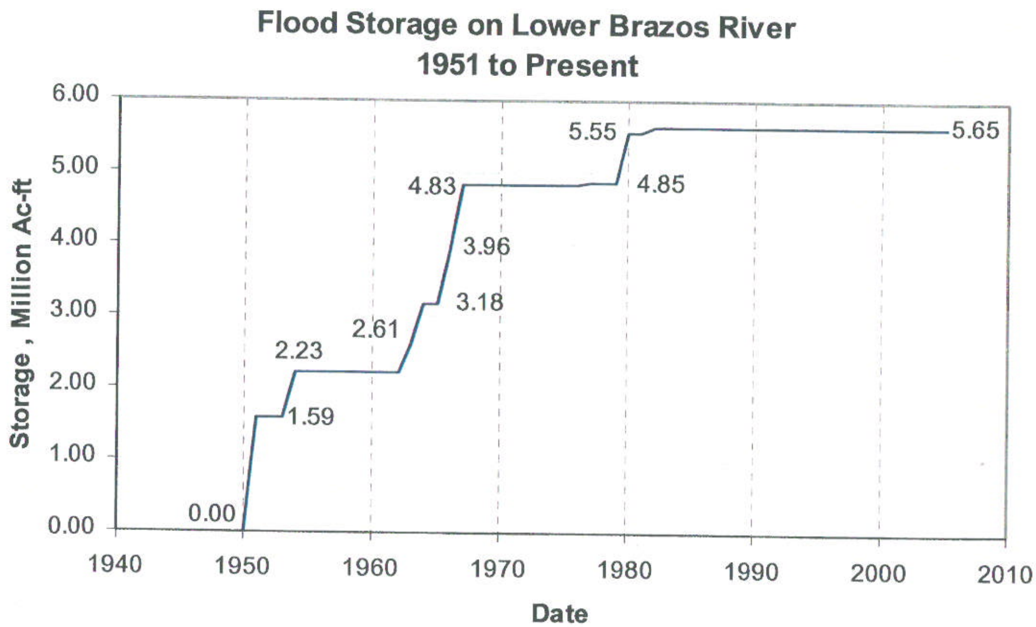
[4] U.S. Department of the Interior and USGS, Indications and potential sources of Change in Sand Transport in the Brazos River, Texas, Water-Resources Investigations Report 01-4057

only about 2 percent of the reservoirs each had over 5000 acre-feet of conservation storage capacity and 13 of the reservoirs provided 2.8 million acre-feet of flood control storage. Between 1940 and 1969, the reservoir conservation storage in the Brazos River basin increased from approximately 258,700 acre feet to approximately 4.8 million acre-feet, or more than 1700 percent, as shown below.



After 1969 to approximately 1995, the rate of increase slowed to about 16 percent, increasing to approximately 5.6 million acre-feet.

Although approximately 87-years of flow records are available for the Brazos River in Fort Bend County, Texas, the procedures for estimating flood frequencies in the lower Brazos River basin are complicated due to the construction of the major flood-control reservoirs throughout the basin between 1951 and 1980. Frequency analysis assumes a stationary data sequence. Construction of the flood-control reservoirs has introduced non-stationary data. Annual maximum discharge estimates using the pre-reservoir data, or analysis of the non-stationary data would, therefore, not be accurate estimates of the annual maximum discharge that would occur under the current watershed conditions. Section 3 of this report presents the method used to adjust the recorded discharge data to a uniform (unregulated) watershed condition.

1.5 Effective Flood Insurance Study

The February 1977 report, Flood Plain Information, Brazos River, Fort Bend County, Texas, prepared by the USACE (Corps Report) at the request of the Fort Bend County Commissioners Court established a 1-percent annual chance discharge in the Brazos River of 210,000 cfs. The study used stream flow records collected at the Richmond and Juliff gages, flood data from the Texas Water Development Board (TWDB), Fort Bend County Drainage District (FBCDD), and Dow Chemical Company, and flood stages at the Richmond Railroad Bridge from the Texas and New Orleans Railroad Company.

When the Fort Bend County FIS was being prepared by Espy, Huston & Associates, Inc. (EHA) in the early 1980's changes had been made by the United States Water Resources Council in the methods used to determine flood flow frequency and changes in the estimates of historical flood flows in the Brazos River. These changes precipitated a reassessment of the 1-percent annual chance discharge at the Richmond gage. The recommended 1-percent annual chance discharge resulting from the reassessment was 181,000 cfs. Before determining the analysis methods that would be used for this study, the EHA method was reviewed to determine if it should continue to be used to establish the updated flood frequency curve for the Brazos River in Fort Bend County.

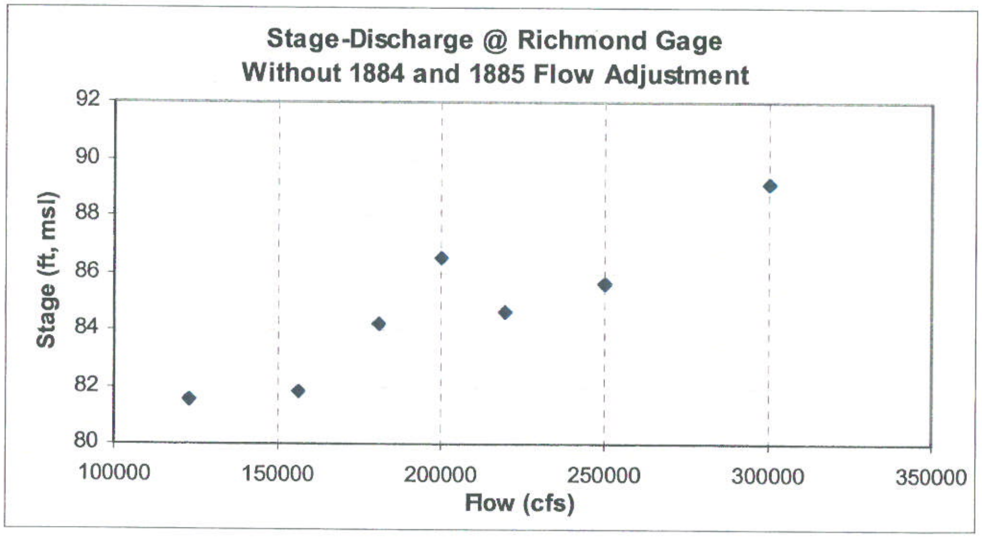
1.5.1 Espy-Huston Approach

The procedure used by EHA to estimate the flood frequencies for the Brazos River FIS used the following steps:

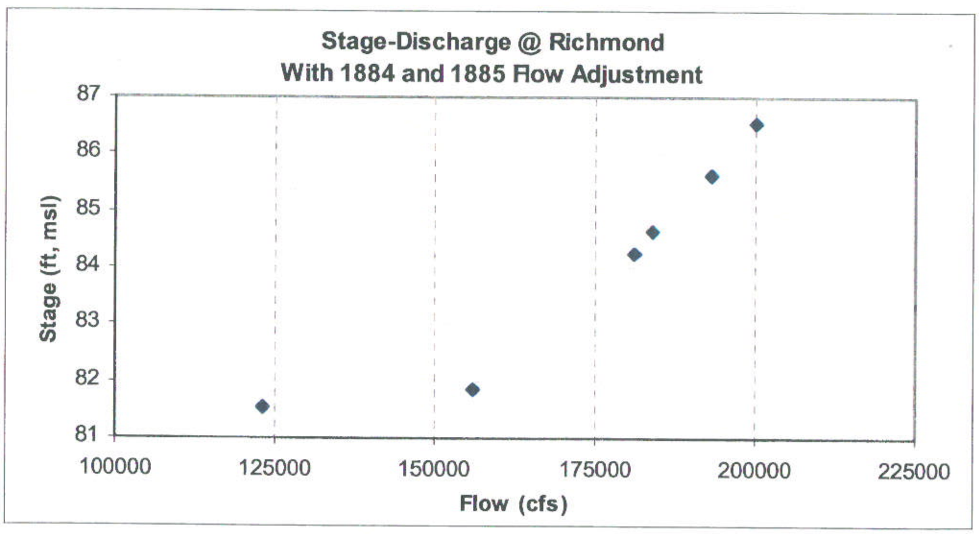
5. Estimate the unregulated annual peak flows from gage records for years subsequent to reservoir construction by routing daily changes of reservoir storage to the Richmond gage and adjusting the recorded peak discharge by adding the net change in storage.
6. Compute the flood frequency curve as recommended in Bulletin 17B
7. Develop a HEC-1 computer model of the Brazos River watershed that results in the unregulated frequency estimates.
8. Use the "calibrated" HEC-1 model to route the unregulated hydrographs through the reservoirs existing in 1984 to obtain the regulated frequency curve.

The basic premise of the EHA study was that construction of the reservoirs introduced an effect into the measured data; however, the report did not present any graphical representation or statistical testing of the data. Graphical analysis would be a reasonable first step in analyzing the available annual maximum flow data. Subsequent statistical tests should then be used to decide whether a significant effect actually does exist.

The Corps Study lists the peak discharge for the May 1884 and June 1885 events as 220,000 cfs and 250,000 cfs, respectively. The EHA Report corrected the flow estimates for the 1884 and 1885 floods to 184,000 cfs and 193,000 cfs, respectively, since the reported stages were less than the 1899 flood, which had a flow of approximately 200,000 cfs and was consistent with other flood estimates. This is illustrated in the following charts that show the stage-discharge at Richmond with, and without the flow adjustment.



The adjustment to the 1884 and 1885 flows were made interpolating linearly between the estimated peak flows and gage heights recorded for the 1899 and 1915 floods.



The 1-percent annual chance flow at the Richmond gage for unregulated conditions presented in the EHA Study was 238,000 cfs. Table 1.5 shows the adjustments made to the recorded peak flows at the Richmond gage, from the Flow Frequency Analysis data presented in the EHA Study.

Table 1.5
Brazos River Richmond Gage
EHA Adjustment of Peak Flows

Water Year	Peak Flow (cfs)		Ratio
	Gage Record	Adjusted to Unregulated	(Record/Adjusted)
1953	83,100	85,682	0.97
1954	32,400	32,400	1.00
1955	19,300	19,300	1.00
1956	17,900	17,900	1.00
1957	119,000	188,401	0.63

Table 1.5
Brazos River Richmond Gage
EHA Adjustment of Peak Flows

Water Year	Peak Flow (cfs)		Ratio (Record/Adjusted)
	Gage Record	Adjusted to Unregulated	
1958	87,600	99,260	0.88
1959	39,200	39,200	1.00
1960	60,300	60,300	1.00
1961	78,800	88,193	0.89
1962	20,600	20,600	1.00
1963	17,400	17,400	1.00
1964	14,400	14,400	1.00
1965	98,800	150,453	0.66
1966	74,400	111,957	0.66
1967	13,400	13,400	1.00
1968	89,600	127,037	0.71
1969	58,100	58,100	1.00
1970	47,800	47,800	1.00
1971	20,100	20,100	1.00
1972	24,400	24,400	1.00
1973	72,500	72,500	1.00
1974	55,300	55,300	1.00
1975	64,000	64,000	1.00
1976	44,300	44,300	1.00
1977	80,500	107,221	0.75
1978	16,100	16,100	1.00
1979	88,100	104,521	0.84
1980	45,500	45,500	1.00
1981	64,700	64,700	1.00
1982	61,300	61,300	1.00

As shown in Table 1.5, not all of the peak flows for the regulated period of record were adjusted to account for reservoir storage. Footnotes to Table 2 in the EHA Study indicate that the unregulated flow was determined using the daily changes in reservoir storage routed to the Richmond gage, however, the documentation of the reservoir storage and the routing were not included with the report. This lack of documentation made it difficult to replicate the EHA adjustment to the unregulated condition, as discussed in Section 3.

To determine the 1-percent annual chance flow at the Richmond gage to regulated conditions, EHA prepared a rainfall-runoff model of the Brazos River basin between Possum Kingdom Reservoir and the Richmond gage using the USACE HEC-1 computer program. The 100-year, 6-hour point rainfall amounts from the U.S. Weather Service Technical Paper 40 (TP-40), "Rainfall Frequency Atlas of the United States" were reduced to convert the rainfall aerially. The maximum rainfall adjustment for a six hour rainfall in TP-40 is for an area up to 400 square miles, which is considerably less than the 21,411 square mile area of the Brazos River basin between Possum Kingdom Reservoir and the Richmond gage. Therefore, EHA based the adjustment factor on the ratio that would yield the 1-percent annual chance flow that had been determined from the flow frequency analysis (238,000 cfs).

To determine the 1-percent annual chance flow at the Richmond gage for regulated conditions, the flow was routed through eight reservoirs (Whitney, Proctor, Belton, Stillhouse Hollow, Waco, Georgetown, Granger and Somerville) that were added to the HEC-1 model. The reservoir routings were made using the modified Puls method, with the initial stage at the top of each conservation pool and using zero flow except for spillway flows at stages above the top of flood control pools. The results of the HEC-1 model indicated a regulated 1-percent annual chance flow at the Richmond gage of 181,000 cfs. The EHA analysis assumed the flow was constant through Fort Bend County.

Additional investigation establishing the validity of the EHA analysis is presented in Section 4.

2.0 DATA SOURCES

2.1 General Description of Flood Frequency Data

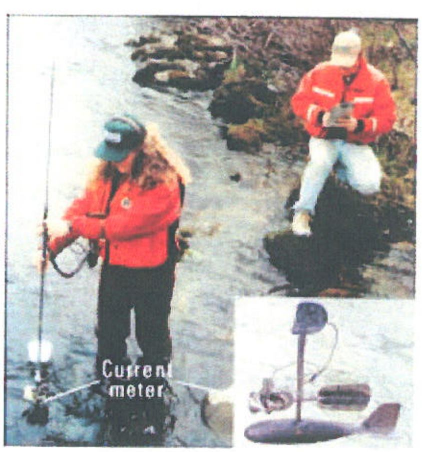
Many types of data can be used to estimate flow or exceedance probabilities for the Brazos River in Fort Bend County. These include systematic streamflow and precipitation data, historical data, and regional hydrological analysis of extreme events. Flood frequency analysis is usually based on systematic streamflow, or precipitation records with rainfall/runoff modeling. For Log-Pearson III analysis, historical flood data can also be considered, which can provide information about flooding over longer periods of time than just the systematic records and could increase the accuracy of the frequency analysis.

2.1.1 Systematic Streamflow Data

The USGS has the primary responsibility for operating a network of streamflow gaging stations throughout the United States as part of a cooperative effort between Federal, State, and local agencies. The streamflow data is used for many purposes, which include flood and drought forecasts, dam control and hydropower generation, and land use and climate change effects, among others.

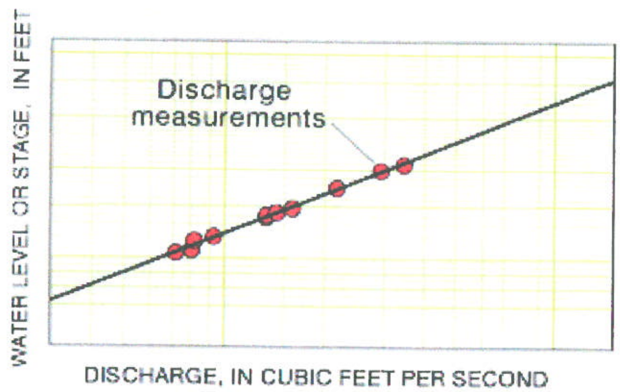
The gage height (or stage) of a river is most commonly measured through the use of a stilling well or a bubble system. The well is connected to the stream with pipes such that when the water level changes in the stream, the level simultaneously changes in the well. A float in the well is then connected to a recorder or data collection platform. An outside reference gage, typically a horizontal graduated ruler called a staff gage or inclined staff gage, is read periodically to verify that the recorded gage heights from the stilling well are the same as the water level in the stream.

The volume of water passing a specific point in a given interval of time is called streamflow discharge and is generally measured in cubic feet per second. The station does not directly measure discharge, so it must be determined by making measurements of the cross section area of the river and how fast water is flowing (velocity) past that section. Discharge is calculated by multiplying the width, depth, and average velocity of the section of the river.



Velocity is measured by using a current meter as shown on the left. The meter consists of cups that are rotated by the action of flowing water. The speed of the rotation depends on the velocity of the water passing by the cups. A technician records the number of revolutions in a given time interval and determines the velocity at the location of the meter. The stream is divided into segments and average velocity and depth of the stream are measured at each segment. The discharge in each of the segments is then summed to obtain the total stream discharge.

A stage-discharge relation or rating curve is used to relate river level to associated streamflow discharge. The rating curve for a specific stream location is developed by making successive discharge measurements in order to define and maintain a stage-discharge relation. These discharge measurements and their corresponding stages (or gage heights) are then plotted on a graph for each station. Continuous discharge throughout the year can be determined from the rating curve. Factors such as debris and vegetation growth can affect the stage-discharge relation and the data must be checked periodically to ensure accuracy.



Example Rating Curve
(from USGS website)

A copy of the rating curve for the Brazos River at the Richmond gage is included in Appendix A.

2.1.2 Precipitation Data

Rainfall data are collected through a nationwide network of rain gages, and more recently, using radar and satellite imagery. The National Weather Service maintains a network of meteorological stations in the United States and precipitation data are published by the National Oceanic and Atmospheric Administration (NOAA). Digital precipitation records can be obtained from the National Climatic Data Center. Other sources of extreme precipitation information are the USACE, and the USGS.

2.1.3 Historical Flood Data

Historical data are observed flood stages or conditions that were made before systematic data collection began. This type of data are obtained from a variety of sources, including newspaper reports, and personal observation. The USGS has compiled levels of flooding that have not been exceeded at a given location over a known period of time.

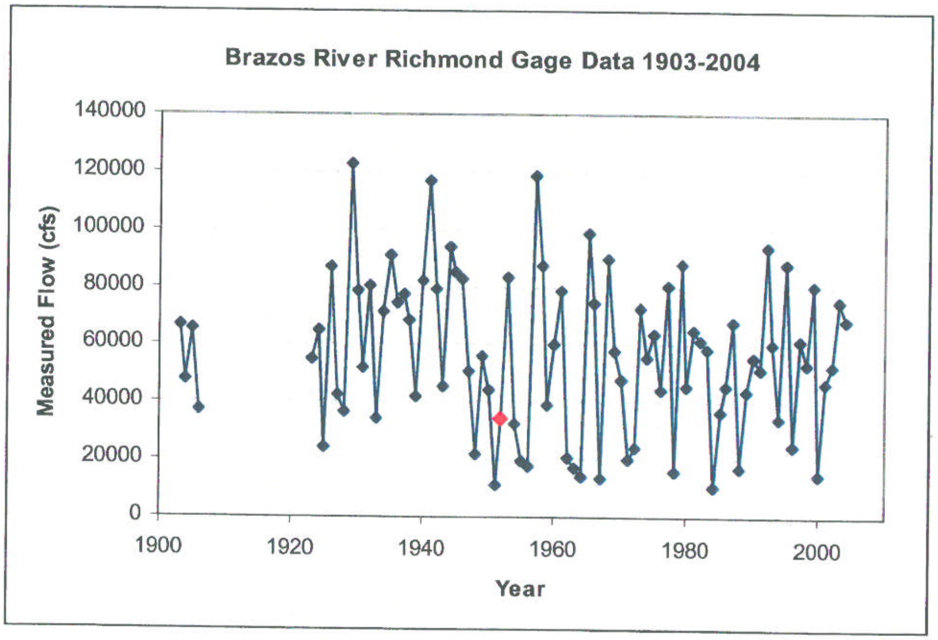
In statistical terms, historical data are usually treated as censored samples. Since historical descriptions of storms and flood events are sometimes exaggerated and contradictory, the information should be carefully reviewed. Using historical data in a flow frequency analysis has the following problems:

- Estimates of peak flood discharges associated with historical flood stage are subject to error.
- An erroneous conclusion that a given flood level has not been exceeded over a known period of time.
- Using systematic data with the assumption that it is homogeneous.

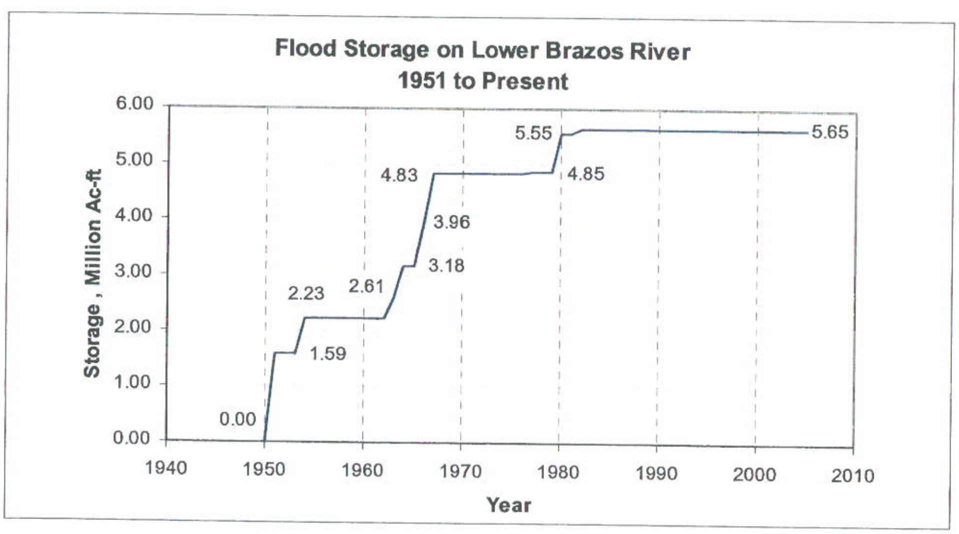
The errors in historical peak flood discharges can be minimized by explicitly accounting for them in the analysis, however, using an erroneous flood level as not being exceeded over a known period of time cannot be accounted for statistically. Using non-homogeneous systematic data is problematic because the hydrologic impacts that occurred during the early history of the United States and the lack of systematic data with which to assess the impacts.

2.2 Brazos River Data

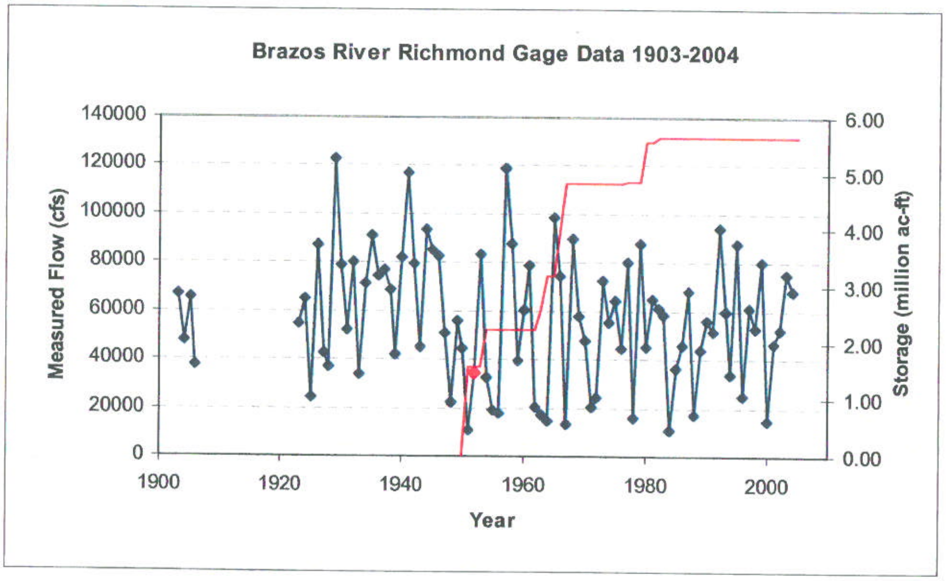
The most important data set used for the flood frequency analysis of the Brazos River at Richmond is the annual peak discharge data compiled by the USGS (Station 08114000 with a drainage area of approximately 45,007square miles, of which 9,566 square miles is probably noncontributing). The maximum annual peak flows, uncorrected for the upstream reservoirs, for water years 1903 through 1906 and 1923 through 2004 are shown below.



Flood storage volume constructed on the Brazos River beginning in 1951 is shown below:



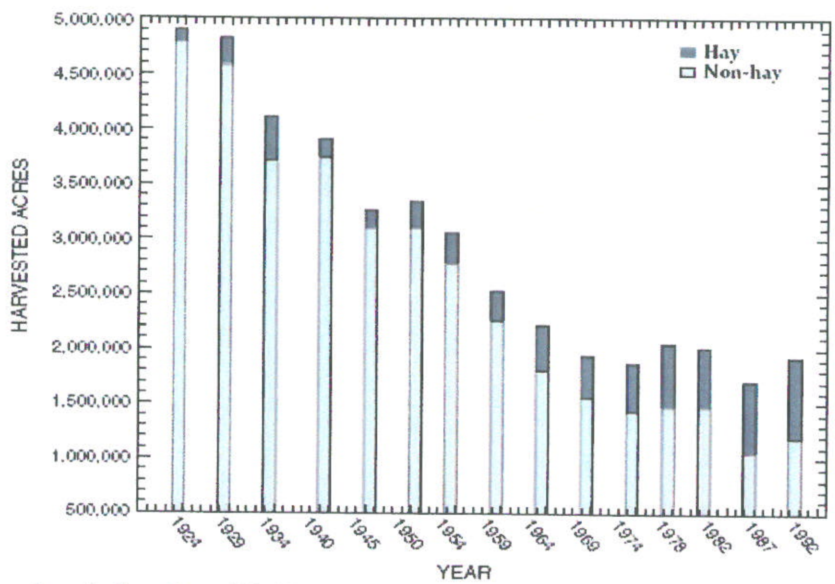
When the two graphs are shown together, it appears that, as the amount of upstream storage increased, the level of the peak flows occurring at the Richmond gage decreased.



2.2.1 Historic Activities in the River Basin

Before considering the historical flood data, it is instructive to review the history of land usage within the Brazos River basin. Changes in land use in a river basin will alter the amount of rainfall runoff reaching the channel. Poor agricultural practices can increase runoff. During the 19th and early 20th centuries, the amount of land in the Brazos River basin that was used for agriculture increased substantially. Land that was originally forested was cleared first for pasture, then to grow row-crops such as cotton, corn and sorghum, and in Fort Bend County, sugar cane.

The total area of harvested acres of non-hay crops decreased more than 75 percent between 1924 and 1992, from about 32 percent to about eight percent of the total area. The following chart shows the total acres harvested in the 27 counties in the lower Brazos River basin.



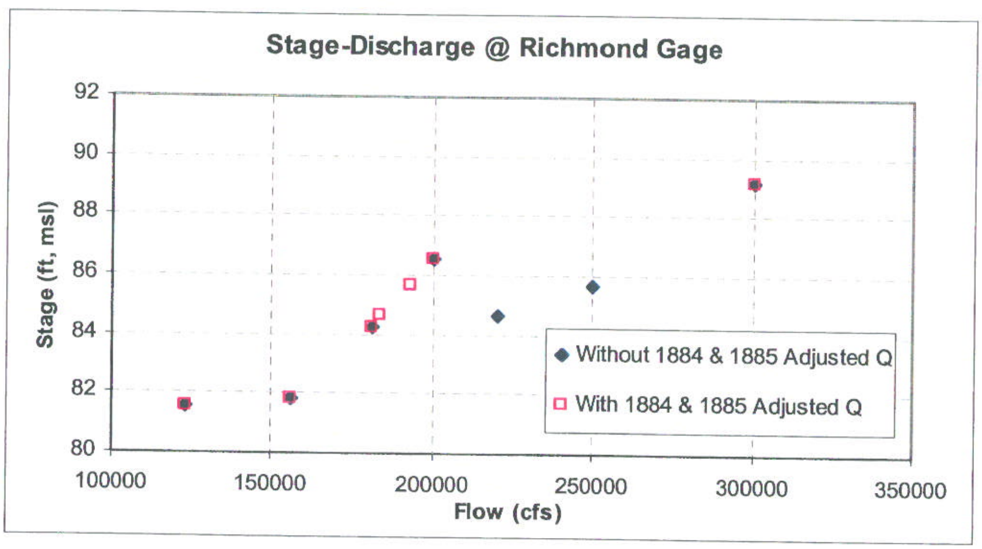
USGS Water-Resources Investigations Report 01-4057

In the early years of sugar cane production, levees were built along the Brazos River in Fort Bend County to protect the crops. Since the late 1970's, the levees have been built to reclaim the effective floodplain for residential and commercial development. Beginning at approximately river mile (RM) 62, upstream to RM 88.3, except for occasional drainage and outfall channels, the northern bank of the Brazos River has a continuous levee. On the southern bank, levees have been built from approximately RM 83.6 to RM 84.2.

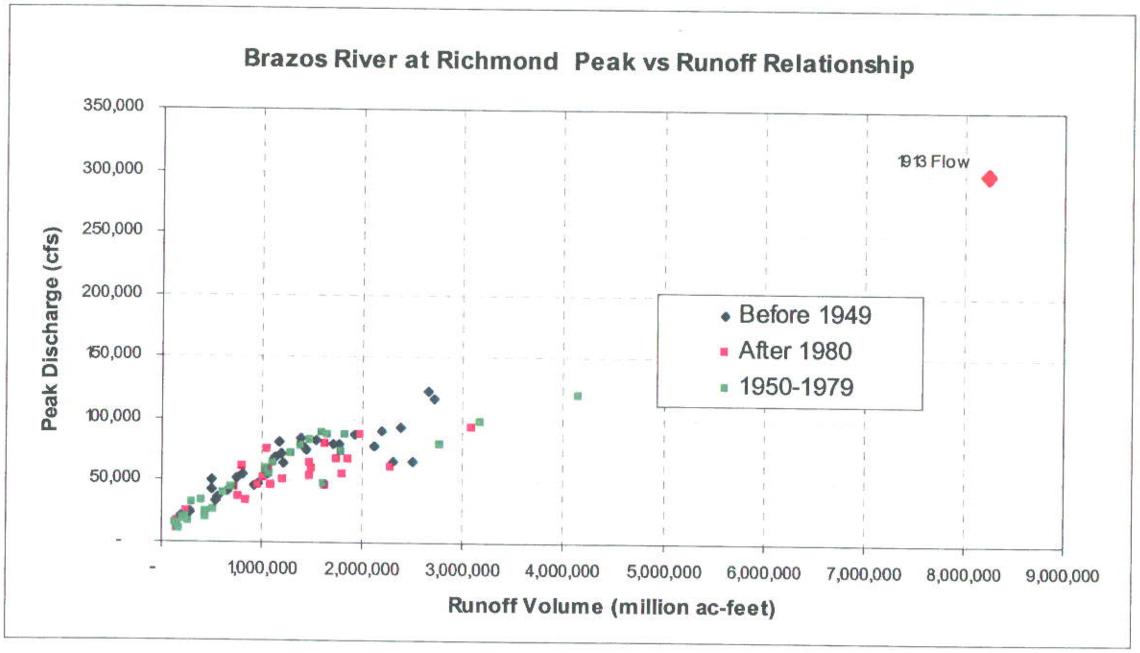
2.2.2 Historical Data

Observations of historical floods on the Brazos River in Fort Bend County, Texas date from the mid-1800's. Based on information gleaned from old newspaper articles, the station description for the USGS gage at Richmond, Texas states that the maximum stage since at least 1852 is that of December 10, 1913. Additional historical stage data shown for May 1884, June 13, 1885, and July 1899 obtained from the Southern Pacific Railroad Company at a point approximately 925 feet upstream from the present gage, shows gage heights of 43.7, 44.7, and 45.6 feet, or flood stages of 84.64, 85.64, and 86.54 feet, respectively. The December 1913 flood is considered the flood of record, with a gage height of approximately 48.2 feet, or flood stage of approximately 89.14 feet.

Flows for the 1884, 1885, and 1913 historical events were estimated by the USACE as approximately 220,000, 250,000, and 300,000 cfs, respectively. As shown below, the following chart, adjusting the 1884 and 1885 flows by interpolating linearly between the estimated peak flows and gage heights recorded for the 1899 and 1915 floods, results in more reasonable flow estimates.



A hydrograph of the 1913 flood is available and, as shown in the following chart graphing the annual peak flow versus the runoff volume for the peak event, has a much higher runoff volume than any other measured event.



2.2.3 Summary

More than 80 years of flow data is available for the USGS gage 08114000 for the periods of record before and after the construction upstream reservoirs that can be used in the flood frequency analysis of the Brazos River in Fort Bend County. Due to the reservoir construction, however, it is necessary to determine a method for adjusting the annual peak flows to obtain a homogeneous sampling of the data to use in a log-Pearson III frequency analysis. The method used to adjust the peak annual regulated flows to un-regulated conditions is described in Section 4.

3.0 FLOOD FREQUENCY ESTIMATES

3.1 Introduction

Effective planning and design of flood risk management projects require accurate estimates of flood risk. Such estimates allow a quantitative balancing of flood control efforts and the resulting benefits, and also enhance the credibility of floodplain development regulations. These considerations are critical in Fort Bend County, where billions of dollars of property are at risk from flooding.

While the Brazos River flood record at the Richmond gage is over 80 years in length, as a participant in the National Flood Insurance Program (NFIP), Fort Bend County, and the incorporated areas, have the responsibility of providing flood protection for a flood event having a one-percent chance of being equaled or exceeded in any one year. This requires extrapolating beyond the available data as well as smoothing the empirical frequency curve to obtain a more consistent and reliable estimate of the 100-year flood.

A variety of distribution functions and estimation methods are available for estimating a flood frequency distribution. The guidelines for flood frequency analysis presented in Bulletin 17-B was established to provided consistency in the federal flood risk management process.

3.2 Bulletin 17-B

The recommended technique for flood frequency analysis is based on fitting a Pearson type III analysis to the base 10 logarithms of the peak discharges. The flood flow (Q) associated with cumulative probability (p) is then

$$\log[Q_p] = \overline{X} + K_p S$$

Where $\overline{X}$ and S are the sample mean and standard deviation of the base-10 logarithms and K_p is a frequency factor that depends on the skew coefficient and selected exceedance probability. The mean, standard deviation, and skew coefficient of station data are computed using:

$$\hat{\mu}_x = \overline{X} = \sum_{i=1}^{n} x_i / n$$

$$\hat{\sigma}^2 = S^2 = \sum_{i=1}^{n} \left(x_i - \overline{X}\right)^2 / (n-1)$$

$$\hat{\gamma}_x = G = n \sum_{i=1}^{n} \left(x_i - X^3\right) / (n-1)(n-2) S^2$$

3.2.1 Estimation of Skew Parameter

The skew coefficient of the station record (station skew) is sensitive to extreme events, so it is difficult to obtain accurate skew estimates from small samples. The estimate of the skew coefficient can be improved by weighting the station skew with a generalized skew estimated by grouping information from nearby sites. Assuming that the G_g is unbiased and independent of station skew coefficient, the mean square error (MSE) of the weighted estimate is minimized by weighting the station and generalized skew coefficients individually proportional to their individual mean square errors as follows.

$$G_w = \frac{G_s / MSE_{G_s} + G_g / MSE_{G_g}}{1 / MSE_{G_s} + 1 / MSE_{G_g}}$$

Where:

G_w	=	weighted skew coefficient
G_s	=	station skew coefficient
G_g	=	generalized regional estimate of the skew coefficient
MSE[ ]=		the mean square error of the indicated variable

In the absence of detailed studies, the generalized skew coefficient (G_g) for sites in the United States can be found in 17B, however, the use of the skew map should be consistent with the data used to develop it. The map was developed with data from watersheds smaller than 3000 square miles and with essentially unregulated peak discharges. The Bulletin 17B map should not be extrapolated to drainage areas greater than about two or three times the size of the basins for which the map was developed.

3.2.2 Outliers

Bulletin 17B defines outliers as "data points which depart significantly from the rend of the remaining data. Keeping, modifying, or deleting outliers can significantly affect the statistical parameters computed from the data, especially for small samples. High outliers are retained unless historical information is identified indicating that those floods are the largest in a period longer than the systematic record.

Low outliers pose a problem because, due to the log transformation, one or more unusually low flow values can distort the entire fitted frequency curve. Low outliers are detected using the following equation:

$$X_L = \overline{X} - K_N S$$

where X_L is the low outlier threshold in log units, S is the standard deviation of the samples, and K_N is the ten-percent significance values for a normal distribution based on the sample size N.

If an adjustment to for historic flood data has been made previously, then the following equation is used to detect low outliers:

$$X_L = \widetilde{M} - K_H \widetilde{S}$$

where X_L is the low outlier threshold in log units, $\widetilde{S}$ is the historically adjusted standard deviation, $\widetilde{M}$ is the historically adjusted mean logarithm, and K_H is the ten-percent significance value for the period used to compute $\widetilde{M}$ and $\widetilde{S}$.

Bulletin 17B procedures do not involve eliminating outliers. High outliers are retained in the analysis as systematic peaks if usable historic information cannot be found. If historical information is available, then the high outlier is properly discounted to a more appropriate time period. Low outliers are counted and their frequency, which is their valid information relative to flood risk, is used to properly account for the occurrence of low outliers by means of the conditional probability adjustment of a preliminary conditional frequency curve based on the non-outlying observations.

3.2.3 Historical Flood Information

A historical flood is a major flood that occurred outside the period of systematic stream gaging. The stage or elevation of the historical flood is usually determined by high water marks left by the flood that were recorded for posterity. Because the historical event was not observed according to definite statistical sampling criteria, and is not part of the systematic record, its relation to the underlying process of flood occurrence is uncertain. This is so regardless of the accuracy with which the stage and discharge might have been determined. The historical flood cannot be used in flood frequency analysis unless additional information (historical threshold and historical period) is available to relate it to flood occurrence over a historical time period.

Bulletin17B considers information indicating that any flood peaks that occurred before, during, or after the systematic record are maximums in an extended period of time data that should be used in frequency computations. Before the data are used, however, the effects of the reliability of the data, the magnitude of the peak discharge, and changes in watershed conditions over the extended period of time must be thoroughly evaluated. Bulletin 17B recommends a historical flood moment adjustment that effectively fills in the ungaged portion of the historic period and states: "historic information should be used unless the comparison of the two analyses, the magnitude of the observed peaks, or other factors suggest that the historic data are not indicative of the extended record".

Attention must be paid to what is not in the data set as well as to the accuracy of the historical peaks. Accuracy of the length of the historical period is also important because the value is used to compute the amount by which the above-threshold peaks are discounted.

The Bulletin 17B procedure for historical data involves defining the historical threshold discharge that separates the record into two classes of peaks that are given different weights in the computation. The threshold needs to be set at a level high enough to insure that it is not exceeded by any peaks that are not in the record. Any non-systematic peaks that are below the threshold are not are unusable statistically. Although the numerical value of the threshold is not used for computation, setting the threshold to correctly identify the number and magnitudes of the peak to be adjusted is critical to the accuracy of the historical adjustment.

It should not be assumed that any peak that is outside the period of systematic record is a true historic peak in the sense of Bulletin 17B. Occasionally, records contain non-systematic peaks that are lower than many of the systematic peaks and contain few, or no higher non-systematic peaks. Setting too low a threshold will result in improper discounting of the high-magnitude peaks relative to the below-threshold peaks.

3.2.4 Alternative Treatments of Outliers

Outliers can be handled on the basis of censored data. Censoring below a low threshold can eliminate the influence of low outliers.

3.2.5 Censoring

Data quality is important to the validity of the Bulletin 17B frequency analysis. The two broad sets of issues that need to be considered are the relevance of the flood frequency set (and frequency analysis results) to estimation of future flood risk, and accuracy of the data set as a representation of the flood events that actually occurred in the past. Factors such as flow regulation (dams and reservoirs), dam failures, storm water management, effects of development in the floodplain, channel improvements and the effects of mining, forestry or agriculture all have the potential to make all or part of the record unrepresentative of future flood risk.

Regarding the accuracy of the data, most annual peak flows are determined by obtaining the stage or water level at a gage and reading the discharge from a stage-discharge rating curve. The rating curve is made by correlating direct measurements of discharge, made by current meters or similar devices, with concurrent measurements of the water surface elevation. The accuracy of the annual peak flow data depends on the accuracy of the stage reading and the accuracy of the stage-discharge relationship. The accuracy of the stage-discharge relationship depends on the accuracy, number and flow measurements of the direct discharge measurements used to establish the relationship.

4.0 SUMMARY OF APPROACH

Addressing the non-homogeneity of the data was the most important element in estimating the probability distribution of the flood discharges for the Brazos River at Richmond. As shown in Section 2.2, beginning in 1952, reservoir construction in the Brazos River Basin has affected the amount of rainfall runoff reaching the Richmond gage. The following methods of analyzing the affect of the reservoir storage on the Richmond gage data were investigated:

- using double-mass curves to check the consistency of data by comparing data for a single station with that of a pattern composed of data from several other stations in the area
- comparing the Richmond gage data with data for adjacent watersheds of similar size and topography that are not regulated.

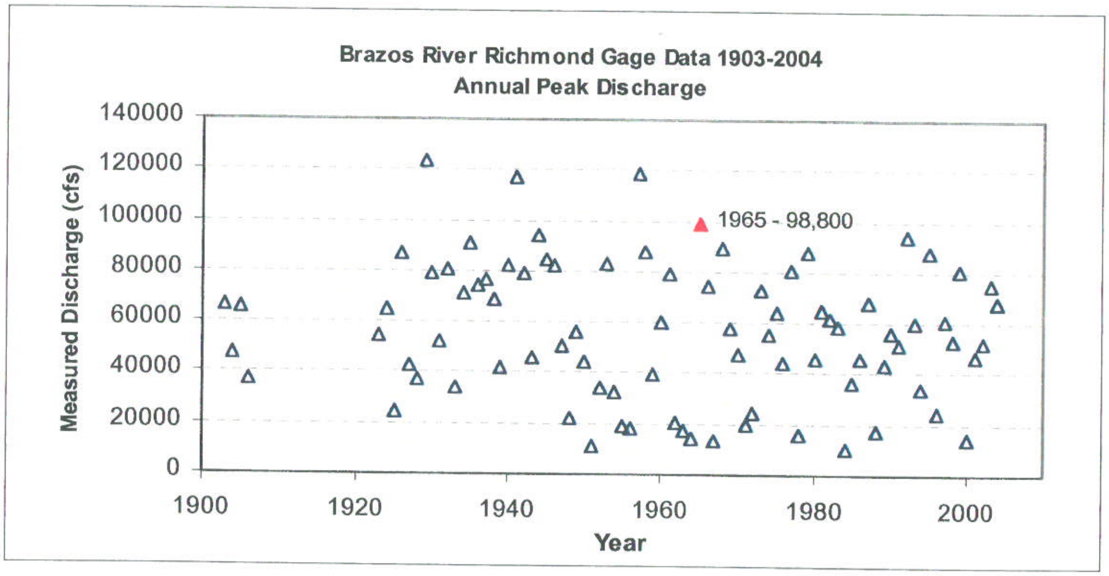
In the end, using these methods did not achieve a reasonable relationship between regulated and un-regulated conditions and the following, simple, method was used to determine a conversion from regulated to un-regulated conditions for the annual peak discharges recorded at the Richmond gage:

- using USGS daily peak flow water data create flow hydrographs for each water year and determine the runoff volume for each annual peak discharge
- determine the reservoir storage volume for each peak event
- combine the runoff volume and storage volume to determine the total runoff volume for the event.
- plot the relationship of total volume versus recorded annual peak flow for the regulated, partially regulated and fully regulated periods.
- develop mathematical equation for the three runoff volume versus peak flow relationships, forcing the equation for the unregulated period through the 1913 flood
- using the equations developed for the unregulated and fully regulated periods, compute the theoretical annual peak flows for the unregulated and fully regulated conditions for the partially and fully regulated period
- using the ratio of the unregulated to regulated theoretical peak flow, adjust the measured flow to unregulated conditions
- further adjust the annual peak flow for the partially regulated period using the percentage of reservoir volume in place at the time of the peak event.

An example of this procedure is shown in the following Section.

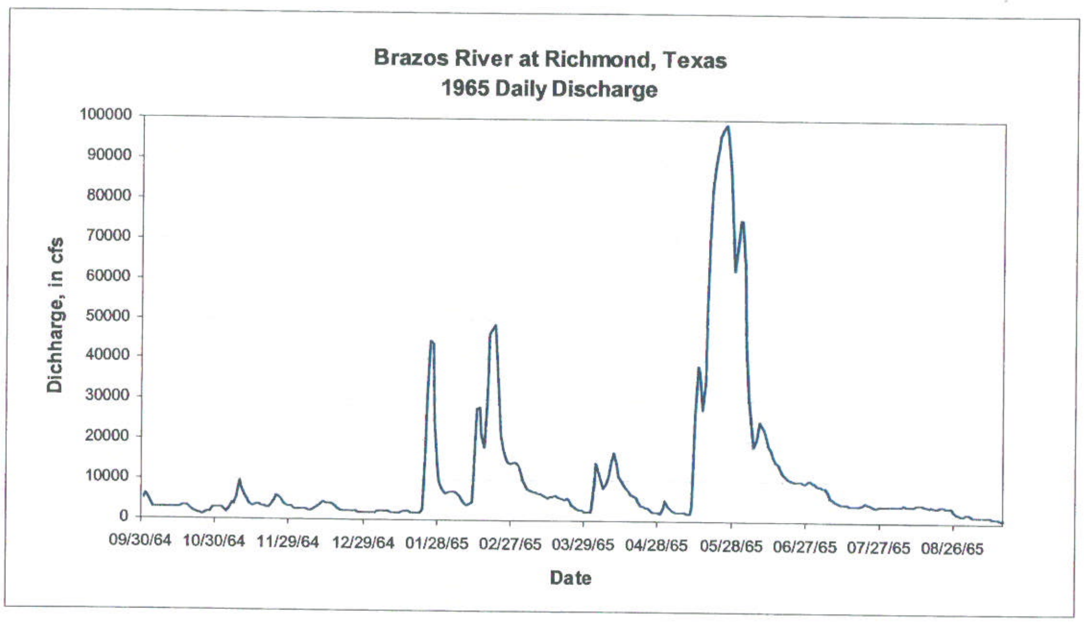
4.1 Peak Annual Brazos River Discharge

The peak annual discharges for the Brazos River at Richmond (USGS gage 08114000) were obtained from the USGS website for the years 1903 to 1906, 1913, and 1923 to 2004. The data used for this analysis is shown in the following chart. The 1965 event, with 98,800 cfs discharge, will be used to illustrate the method used to determine the adjustment from regulated to unregulated conditions.

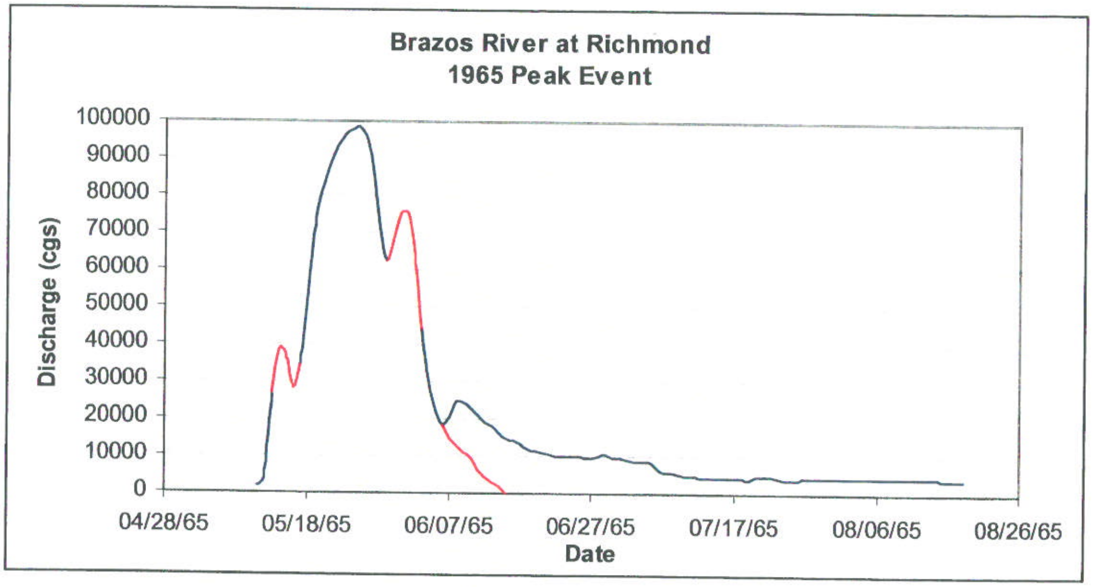


4.2 Runoff Volume for Peak Event

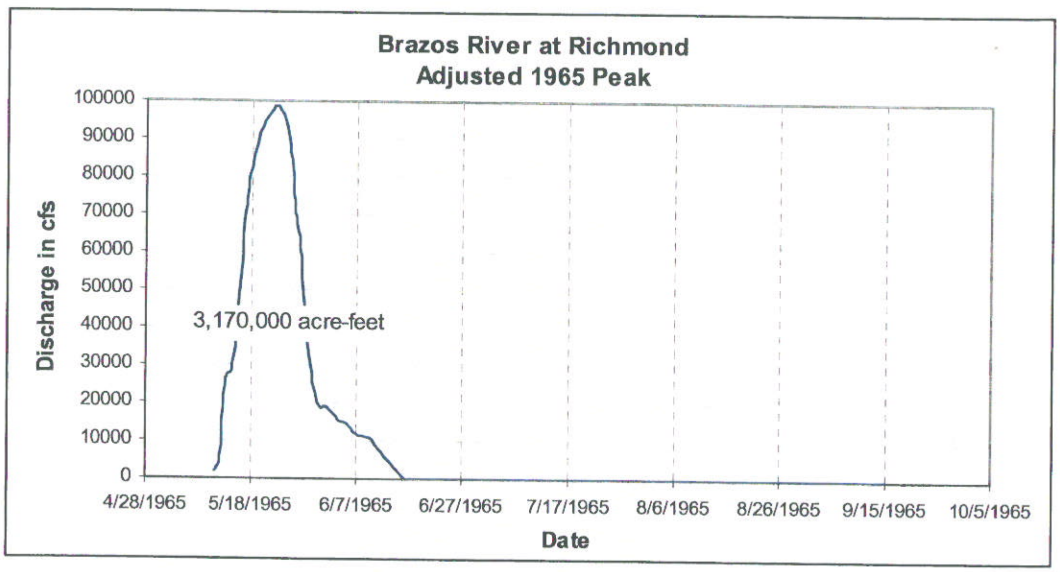
The discharge for the Brazos River at Richmond for water year 1965 is shown in the following chart:



As can be seen, the peak event occurred from about May 11 to about August 18, 1965. This event was then isolated and data for the non-peak event were removed as shown below:



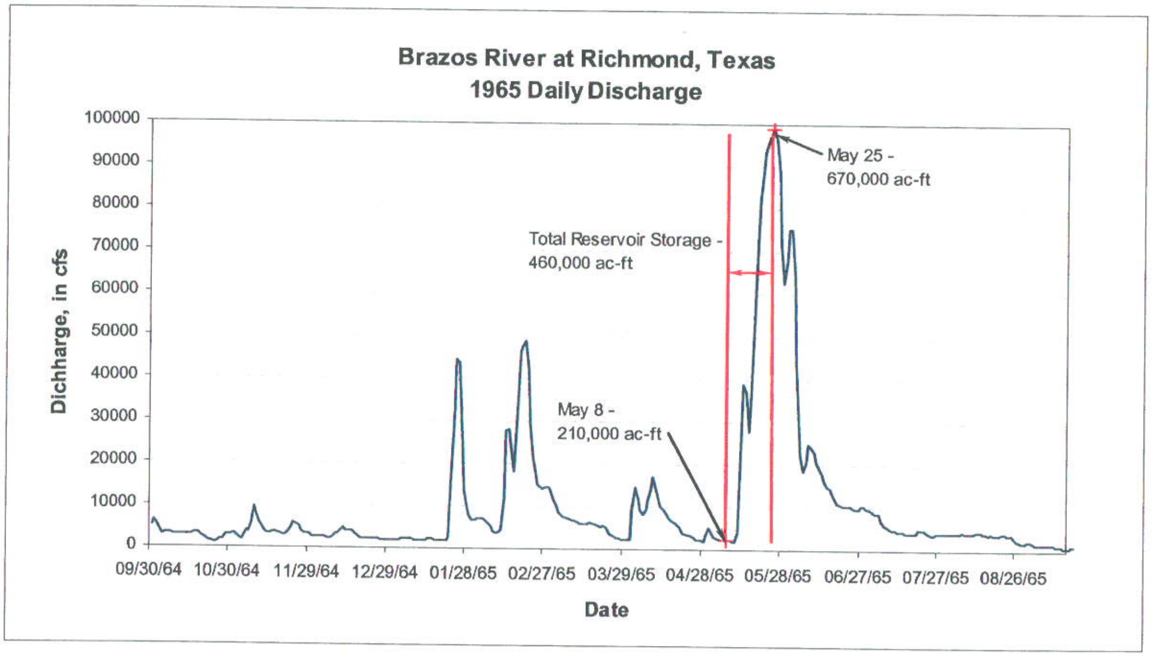
The resulting hydrograph used to compute the runoff volume for the event is shown below:



The volume intercepted by each upstream reservoir was determined using USGS data, as shown for Lake Belton in the following table and chart.

Table 4.1
Lake Belton Reservoir Storage, (Acre-Feet)
Water Year Oct 1964 To Sep 1965

DAY	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1	254500	214500	212400	210700	213000	278100	234500	212400	698200	444600	306500	211300
2	251500	213300	211700	211300	212500	275300	235500	211700	694700	440400	300500	100
3	248400	212200	210800	211400	212800	272400	235900	211000	687100	435800	295500	211000
4	245900	223200	210200	211600	213200	269100	236500	210600	678000	431100	290700	400
5	243400	231900	209800	211600	213700	265200	235300	500	680900	427100	285700	600
6	241000	236000	209600	211800	214100	261300	235000	210100	674200	422800	280700	800
7	238900	236000	209500	211900	214700	256500	900	209900	666500	418700	275700	900
8	236700	235500	209600	211900	215700	252200	235300	210100	658300	414900	270800	900
9	233500	233000	210500	211900	235300	247800	232500	210800	650500	410900	266000	900
10	229500	229000	211000	211300	245100	243700	229700	217900	642300	407100	261200	700
11	224900	225200	211500	210600	256800	239400	226900	241300	633100	402800	256700	600
12	220400	221400	211900	210300	265500	235100	222900	250800	624200	398400	251400	600
13	215600	218200	212100	209900	267600	230800	218100	261000	615400	394800	246300	500
14	212700	216200	212100	209700	267900	226400	214200	281200	605700	390300	241300	300
15	211300	214700	211900	209700	266900	221900	212400	297000	597300	385800	237200	211000
16	210800	213300	211800	209400	270800	217700	211700	474200	587100	381200	232900	210800
17	210800	211800	211300	209700	275600	213600	211000	552200	578000	376500	228200	211000
18	210800	210600	210600	210200	279800	211500	210600	589300	568800	372100	223200	210900
19	210800	212100	210200	210300	282600	210900	210000	618800	559000	367500	218500	211100
20	210800	213700	209900	210700	283700	210200	209500	639600	549500	362800	215800	0
21	210800	214000	209900	214200	284400	209600	700	652900	539800	357300	800	211800
22	210900	213700	209900	221200	284100	209900	209900	659900	530600	353000	600	219500
23	210900	211700	210100	225500	284600	210600	210200	665700	520900	348800	215500	222700
24	210900	210300	210300	226800	284200	211400	300	670300	511600	344400	214700	223500
25	211000	211100	210400	227800	283700	212200	210800	674200	501600	339700	212500	600
26	213300	212500	210500	226700	282700	212700	212100	676600	491600	335000	211000	223700
27	214600	213200	210400	223900	281200	212500	212800	675500	482000	330300	210800	221400
28	215400	213700	210500	220000	279600	212400	213100	685100	471800	325700	700	216700
29	216200	214000	210500	217500	---	221800	400	689800	461100	320700	400	211600
30	216000	213400	210700	215900	---	230400	213100	694300	451400	315800	300	208800
31	215200	---	210700	214100	---	233200	---	697700	---	311300	210500	---



The total reservoir storage for the 1965 water year is approximately 927,520 acre-feet for the four reservoirs that were constructed.

Table 4.2
Total 1965 Reservoir Volume (Acre-Feet)

	8-May	25-May	Storage
Squaw Creek Reservoir	Not Built		
Lake Whitney	365,000	560,300	195,300
Aquilla Lake	Not Built		
Waco Lake near Waco	71,280	248,500	177,220
Proctor Lake near Proctor	35,000	130,000	95,000
Belton Lake near Belton	210,000	670,000	460,000
Stillhouse Hollow Lake	Not Built		
Lake Georgetown	Not Built		
Granger Lake	Not Built		
Somerville Lake	Not Built		
	Total Storage	**927,520**	**ac-ft**

The total runoff volume for the 1965 water year peak flood event is, thus, approximately 3,170,000 acre-feet (rounded) plus 927,520 acre-feet, or 4,097,000 acre-feet (rounded).

4.3 Adjustment to Unregulated Watershed Condition

The systematic data was divided into three segments to reflect pre- and post-reservoir data, as follows:

- Unregulated discharge – 1903 to 1952
- Partially regulated discharge – 1952 to 1982
- Regulated discharge – 1983 to 2004

Trend lines were developed for each of the data sets, as shown in Figure 4-1

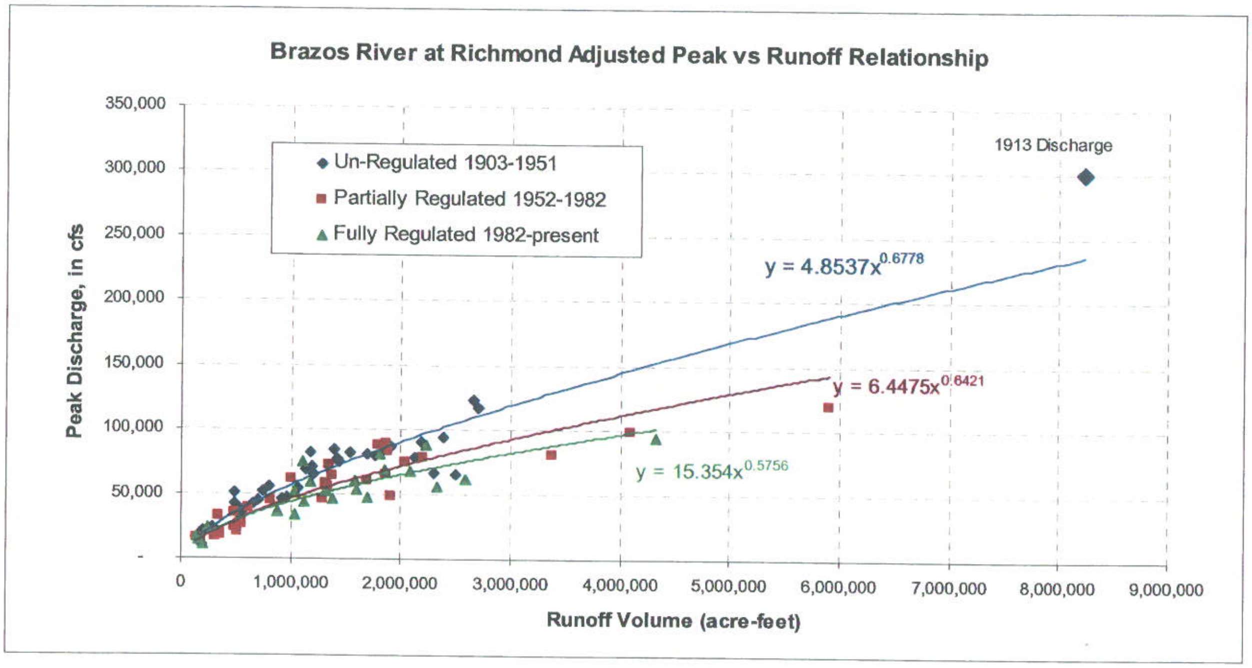


Figure 4-1

The trend line for the unregulated period was adjusted to include the 1913 discharge, as shown in Figure 4-2.

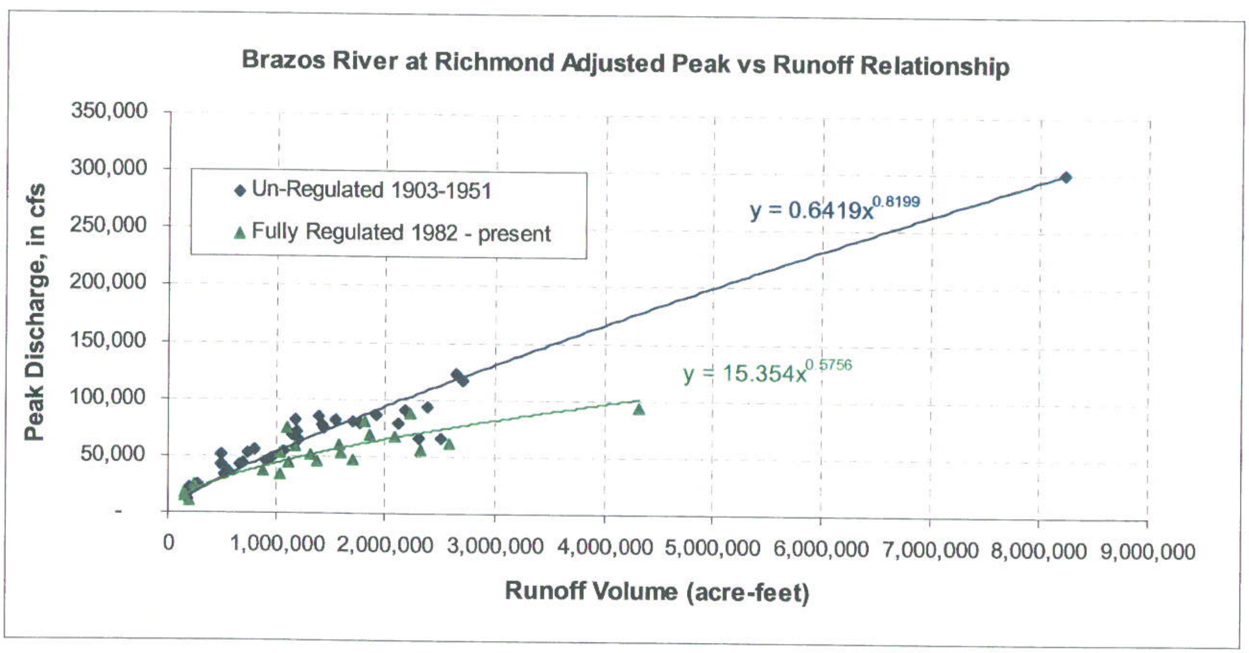


Figure 4-2

The theoretical annual peak discharges for regulated and unregulated conditions were then established as shown in Figure 4-3.

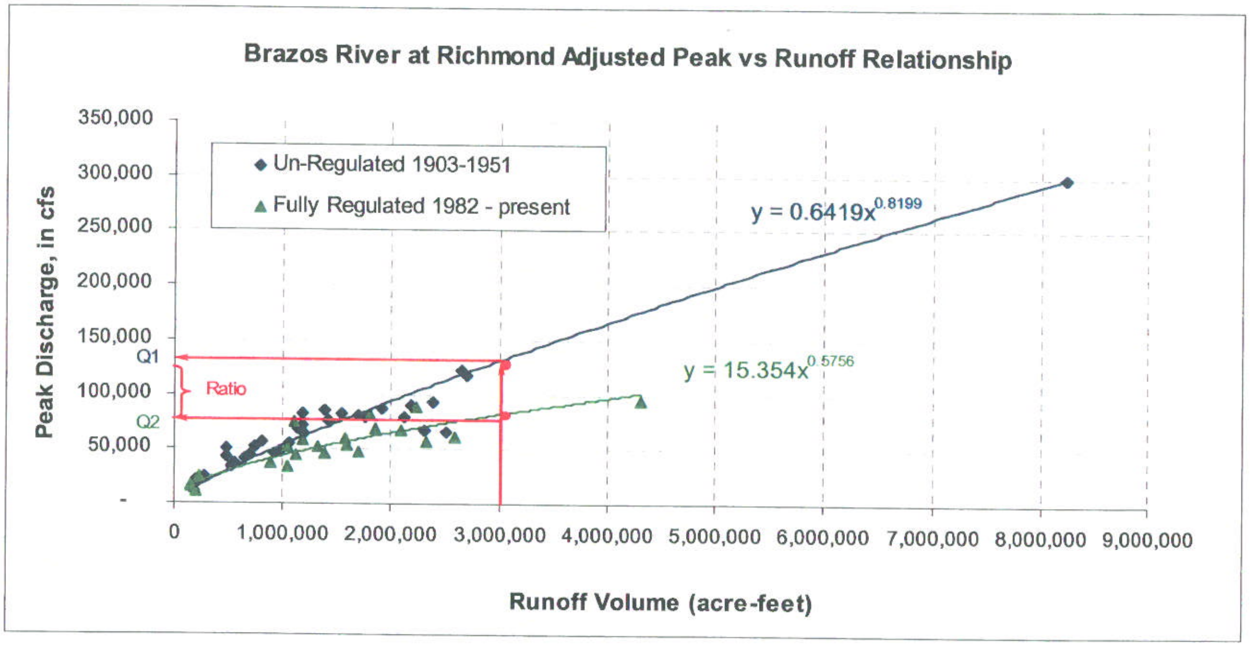


Figure 4-3

Using the volume of discharge for a particular water year, compute a discharge based on the equation of the curve for fully regulated conditions. Compute a second discharge based on the equation of the curve for the unregulated period. Apply the ratio of these two discharges to the actual measured discharge to adjust the regulated discharge to unregulated conditions.

The ratio between the two derived annual peak flows was used to adjust the regulated and partially regulated annual peaks to unregulated conditions as shown in Table 4.3. If the derived conversion factor was less than 1.0, then the annual peak discharge was not adjusted.

Table 4.3
Brazos River at Richmond
Adjustment Ratio to Unregulated Conditions

Year	Recorded Annual Peak Discharge (cfs)	Runoff Volume (ac-feet)	Adjusted to Unregulated Annual Peak (cfs)	Adjusted to Regulated Annual Peak (cfs)	Conversion Factor	Adjusted Annual Peak Discharge (cfs)
1952	34,400	484,000	29,400	28,700	1.024	35,200
1953	83,100	1,879,990	89,500	62,800	1.425	118,400
1954	32,400	342,000	22,100	23,500	0.940	32,400
1955	19,300	359,990	23,100	24,200	0.955	19,300
1956	17,900	358,000	23,000	24,200	0.950	17,900
1957	119,000	5,902,000	228,600	121,200	1.886	224,500
1958	87,600	1,790,000	85,900	61,000	1.408	123,400
1959	39,200	620,000	36,000	33,100	1.088	42,600
1960	60,300	1,688,000	81,900	59,000	1.388	83,700
1961	78,800	2,189,990	101,400	68,500	1.480	116,600
1962	20,600	509,999	30,700	29,600	1.037	21,400
1963	17,400	309,990	20,400	22,200	0.919	17,400
1964	14,400	179,999	13,100	16,300	0.804	14,400

Table 4.3
Brazos River at Richmond
Adjustment Ratio to Unregulated Conditions

Year	Recorded Annual Peak Discharge (cfs)	Runoff Volume (ac-feet)	Adjusted to Unregulated Annual Peak (cfs)	Adjusted to Regulated Annual Peak (cfs)	Conversion Factor	Adjusted Annual Peak Discharge (cfs)
1965	98,800	4,097,000	169,400	98,300	1.723	170,300
1966	74,400	2,040,000	95,700	65,800	1.454	108,200
1967	26,000	564,000	33,300	31,400	1.061	27,600
1968	89,600	1870,000	89,100	62,600	1.423	127,500
1969	58,100	1,324,000	67,100	51,300	1.308	76,000
1970	47,800	1,910,000	90,600	63,300	1.431	68,400
1971	20,100	287,000	19,200	21,300	0.901	20,100
1972	24,400	486,000	29,500	28,800	1.024	25,000
1973	72,500	1,349,000	68,100	51,800	1.315	95,300
1974	55,300	1,342,000	67,900	51,700	1.313	72,600
1975	64,000	1,384,000	69,600	52,600	1.323	84,700
1976	44,300	818,000	45,200	38,900	1.162	51,500
1977	80,500	3,375,000	144,500	87,900	1.644	132,300
1978	16,100	140,000	10,600	14,100	0.752	16,100
1979	88,100	1,870,000	89,100	62,600	1.423	125,400
1980	45,500	1,290,000	65,700	50,500	1.301	59,200
1981	64,700	1,870,000	89,100	62,600	1.423	92,100
1982	61,300	1,000,000	53,300	43,600	1.222	74,900
1983	58,600	1,180,000	61,100	48,000	1.273	74,600
1984	10,600	200,000	14,200	17,300	0.821	10,600
1985	36,400	880,000	48,000	40,500	1.185	43,100
1986	45,600	1,380,000	69,400	52,500	1.322	60,300
1987	67,800	2,080,000	97,200	66,500	1.462	99,100
1988	17,100	150,000	11,300	14,600	0.774	17,100
1989	43,800	1,119,990	58,500	46,600	1.255	55,000
1990	55,800	2,320,000	106,300	70,800	1.501	83,800
1991	51,400	1,320,000	66,900	51,200	1.307	67,200
1992	94,000	4,320,000	177,000	101,300	1.747	164,200
1993	60,100	1,580,000	77,600	56,800	1.366	82,100
1994	34,000	1,039,990	55,100	44,600	1.235	42,000
1995	88,100	2,220,000	102,500	69,100	1.483	130,700
1996	24,700	240,000	16,500	19,200	0.859	24,700
1997	61,200	2,579,990	116,000	75,300	1.541	94,300
1998	53,000	1,590,000	78,000	57,000	1.368	72,500
1999	80,300	1,810,000	86,700	61,400	1.412	113,400
2000	14,600	156,000	11,600	15,000	0.773	14,600
2001	46,700	1,700,000	82,400	59,200	1.392	65,000
2002	52,300	1,040,000	55,100	44,600	1.235	64,600
2003	74,800	1,100,000	57,700	46,100	1.252	93,600
2004	68,300	1,850,000	88,300	62,200	1.420	97,000

For the period of partial regulation, a reservoir correction factor was determined by computing the ratio of reservoir storage existing for each annual peak compared with the ultimate total reservoir storage for fully regulated conditions. Because the total flood storage available in the reservoirs has never been used, the maximum observed storage was used to determine the correction factor for the reservoirs. For example, in 1965 Lake Whitney, Belton Lake, Proctor Lake and Waco Lake were impounding water, with a "maximum observed storage volume" of approximately 2,990,500 acre-feet. The total "maximum observed storage volume" for all reservoirs is approximately 4,179,010 acre-feet. Therefore, the reservoir correction factor for 1965 is 2,990,500 divided by 4,179,010, or approximately 72 percent. The reservoir correction factor after construction of each reservoir is shown in Table 4.4.

Table 4.4
Brazos River at Richmond
Reservoir Ratio for Partially Regulated Conditions

Reservoir	Date of Deliberate Impoundment	Available Flood Storage (ac-ft)	Max Observed Storage (ac-ft)[5]	Date of Impoundment	Reservoir Correction Factor
Lake Whitney	1951	1,688,900	1,568,900	1951	0.38
Belton Lake near Belton	1954	644,000	726,000	1954	0.55
Proctor Lake near Proctor	1963	373,600	323,700	1963	0.63
Waco Lake near Waco	1965	675,200	371,900	1965	0.72
Somerville Lake	1967	868,700	387,500	1967	0.81
Stillhouse Hollow Lake	1968	777,600	418,300	1968	0.91
Squaw Creek	1977	77,000	13,600	1977	0.91
Lake Georgetown	1980	184,120	99,820	1980	0.94
Granger Lake	1980	514,490	202,690	1980	0.98
Aquilla Lake	1983	161,300	66,600	1983	1.00
TOTAL		5,964,910	4,179,010		

For the partially regulated period, the conversion factor was adjusted to reflect the existing reservoir storage that would affect the annual peak discharge according to the following formula:

$$R_P = [(R_F - 1)xA_R] + 1$$

Where:

R_P = Adjustment for Partially Regulated Conditions
R_F = Adjustment for Fully Regulated Conditions
A_R = Reservoir Adjustment Factor

The adjustments to the annual peak discharge for the years 1952 to 1982, which were affected by reservoir construction, are shown in Table 4.5.

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[5] USGS Water-Data Report TX-2004 Volume 3.

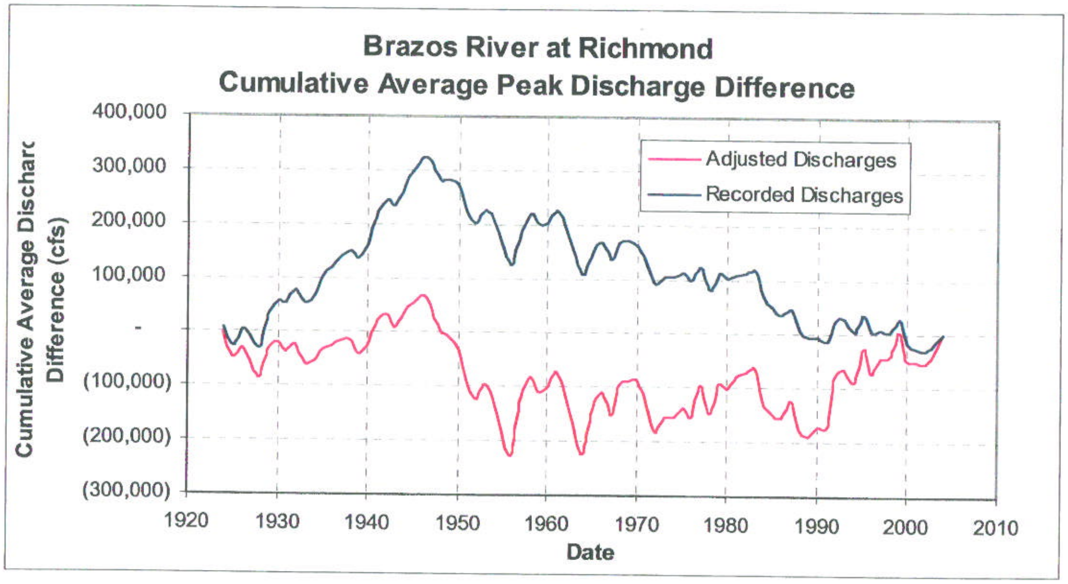
Table 4.5
Brazos River at Richmond
Adjusted Annual Peak Discharge for Partially Regulated Conditions

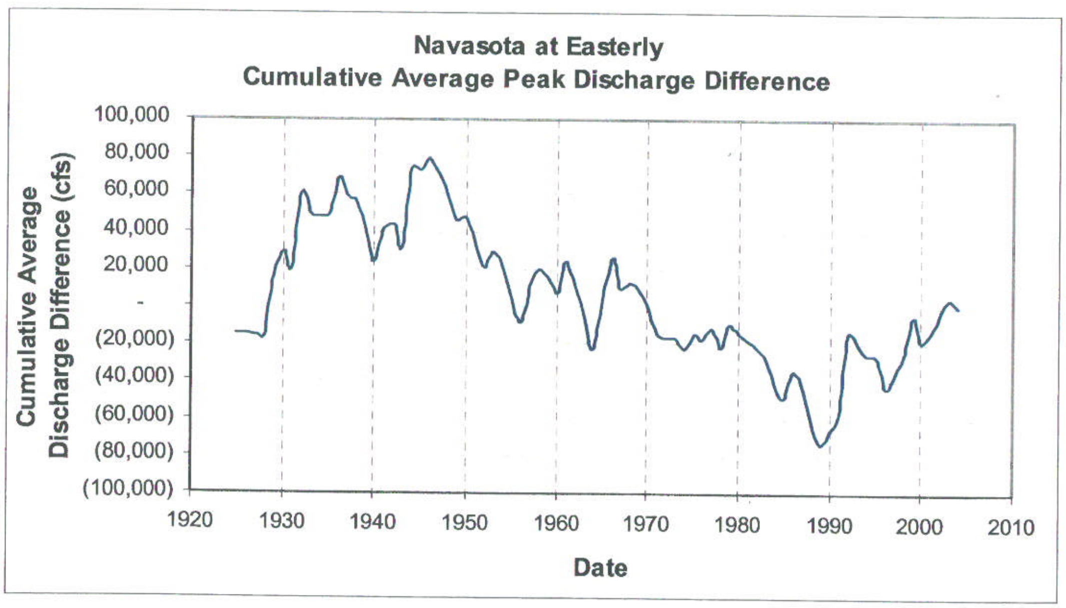
Year	Recorded Annual Peak Discharge (cfs)	Flow Conversion Factor	Reservoir Adjustment Factor	Adjusted Conversion Factor	Adjusted Annual Peak Discharge (cfs)
1952	34,400	1.024	0.38	1.009	34,700
1953	83,100	1.425	0.38	1.162	96,500
1954	32,400	0.940	0.38	0.977	32,400
1955	19,300	0.955	0.55	0.975	19,300
1956	17,900	0.950	0.55	0.973	17,900
1957	119,000	1.886	0.55	1.487	177,000
1958	87,600	1.408	0.55	1.225	107,300
1959	39,200	1.088	0.55	1.048	41,100
1960	60,300	1.388	0.55	1.213	73,200
1961	78,800	1.480	0.55	1.264	99,600
1962	20,600	1.037	0.55	1.020	21,000
1963	17,400	0.919	0.63	0.949	17,400
1964	14,400	0.804	0.63	0.876	14,400
1965	98,800	1.723	0.72	1.521	150,300
1966	74,400	1.454	0.72	1.327	98,700
1966	26,000	1.061	0.81	1.049	27,300
1968	89,600	1.423	0.91	1.385	124,100
1969	58,100	1.308	0.91	1.280	74,400
1970	47,800	1.431	0.91	1.392	66,600
1971	20,100	0.901	0.91	0.910	20,100
1972	24,400	1.024	0.91	1.022	24,900
1973	72,500	1.315	0.91	1.286	93,300
1974	55,300	1.313	0.91	1.285	71,100
1975	64,000	1.323	0.91	1.294	82,800
1976	44,300	1.162	0.91	1.147	50,800
1977	80,500	1.644	0.94	1.605	129,200
1978	16,100	0.752	0.94	0.767	16,100
1979	88,100	1.423	0.94	1.398	123,200
1980	45,500	1.301	0.98	1.295	58,900
1981	64,700	1.423	0.98	1.415	91,500
1982	61,300	1.222	0.98	1.218	74,700

The adjusted annual peak discharge shown in Tables 4.3 and 4.5 were used in the flood flow frequency analysis for the Brazos River at Richmond following Bulletin 17B guidelines, as discussed in Section 5.0.

4.4 Validation of Adjustment Technique

To check the results of the discharge adjustment to unregulated conditions, the annual difference in actual peak flow from the average of the peak flows was plotted for both the regulated and unregulated discharges and compared to the same analysis of the Navasota River at Easterly gage, which was considered to be a comparable basin, without regulation.





Based on the comparison of the two basins, the simplistic method used to convert the regulated peak discharges to unregulated conditions is reasonable. The unregulated condition discharges were then used in a log-Pearson III frequency analysis to develop the one-percent annual discharge at the Richmond gage.

5.0 DATA ANALYSIS

The following data was used to estimate the flood frequency curve:

- Data for the Richmond gage for the period 1903 to 1906 and 1923 to 2004
- Historical data for 1884, 1885, 1899, 1913 and 1915
- 1852 defining the maximum period of record

5.1 Historical Data

As stated in Section 3.2.3, a historical flood is a major flood that occurred outside the period of systematic stream gaging. Since gage data for the Richmond gage dates from 1903 to 1906 and 1923 to 2004, the historical data is data that does not fall in the gaging period. A series of level notes and correspondence prepared by the USGS, beginning in 1931 and continuing from 1944 to 1945 and 1959 are the basis for the historical data presented in the Corps Report. The 1931 level notes established the 1913 flood level by determining the elevation of the top of a piece of timber nailed to a cottonwood tree located on the left bank of the Brazos River that was supposed to mark the elevation of the 1913 flood. The following additional flood marks were established using profiles obtained from the Southern Pacific Railroad (SPRR) at their bridge approximately 1500 feet upstream from the USGS gage. (These stages are not necessarily the highest stage, but the highest observed stage at the SPRR bridge.)

Table 5.1
Brazos River at Richmond
Historical Flood Stages

Date	Elevation in Feet (Railroad Datum)
May 1884[1]	86.4
June 13, 1885	87.4
July 1899	88.3
December 1913	90.2
May 2, 1915	86.0
May 9, 1922	83.6
June 6, 1929	82.9

[1] First flood recorded by SPRR

Initially, the SPRR data was converted to USGS datum using the 1913 flood as a base, since both entities data was considered to be reliable, however, in 1945 the historic flood crests at the SPRR bridge were tied to the USGS gage datum, which established a difference of approximately 42.7 feet between the gage datum and the railroad datum. Other high water marks in the Richmond area were also used to verify the 1913 flood stage.

A 1959 Memorandum to the Houston office of the USGS, established the historical period of record at 1852 using information from Galveston News. The May 29 1884 edition stated "The Brazos River is higher here than it has been in 32 years" for Wallis. An article in the June 6, 1884 edition stated that in Richmond, "the Brazos River commenced falling Tuesday morning and is now slowly receding. It has been about 7 ft higher than at any time since 1852". The available historical data for the Richmond gage is included in Appendix A.

Bulletin17B considers information indicating that any flood peaks that occurred before, during, or after the systematic record are maximums in an extended period of time data that should be used in frequency computations. It was, therefore, necessary to evaluate the historical peak discharges to determine their reliability. The issues of concern include whether the historical sources provide sufficient significant information to associate a stage or discharge with the historic event, whether the historical stage is referenced to the same gage datum as the datum used to develop the stage-rating used to establish the discharge, whether the stage-discharge rating adequately reflects the hydraulic conditions that existed in the channel and floodplain at the time of the historical event. Based on the information discussed above and the documentation included in Appendix A, use of the 1884, 1885, 1899, 1913 and 1915 flood data is appropriate, as is use of 1852 to define the historical period of record.

5.2 Skew Coefficient

A critical parameter in the development of a frequency curve in the Bulletin 17-B context is the skew coefficient, which is a measure or index of the lack of symmetry in a frequency distribution. To stabilize estimates of flood exceedance probabilities Bulletin 17-B provides a skew map that can be used to compute a generalized skew, however, the map was developed with data from watersheds smaller than 3,000 square miles and with essentially unregulated peak discharges. Periods when the annual peak discharge likely differed from natural conditions by more than about 15 percent were excluded from the skew map analysis. The Bulletin 17-B map should not be extrapolated to drainage areas greater than about two to three times the size of the basins for which the map was developed. Because of the size of the Brazos River basin and the length of the flood record, a station skew provides a more reasonable measure.

5.3 Frequency Estimates

The following data sets were analyzed to 1) validate the previous FIS probability distribution developed by EHA, 2) establish updated probability distribution using an additional 22 years of gage data, and 3) devise a method of adjusting the regulated discharge to unregulated conditions that can continue to be used until sufficient gage data is available to provide a probability distribution for regulated conditions.

Table 5.2
Brazos River at Richmond
Flood Frequency Analysis Data Sets

	Description	Skew	Defining Period	Systematic Data
1	Data Used for Fort Bend County FIS	Weighted	N/A	1903-1906 1923-1982
2	Using Simplified Method to Adjust Regulated Data to Unregulated Condition	Weighted	N/A	1903-1906 1923-1982
3	Using Simplified Method to Adjust Regulated Data to Unregulated Condition	Station	N/A	1903-1982 1923-1982
4	Using Additional 22 Years of Gage Records	Station	1852	1903-1906 1923-2004

5.4 Validation of EHA Results

The flood frequency analysis performed for the effective FIS established an unregulated 100-year discharge for the Brazos River in Fort Bend County, Texas of 238,000 cfs. Using the same historical data as was used for the FIS and testing several methods of adjusting the regulated discharges to unregulated conditions resulted in reproducing the EHA results within an acceptable tolerance.

The following chart compares the discharges used for the EHA analysis and this analysis.

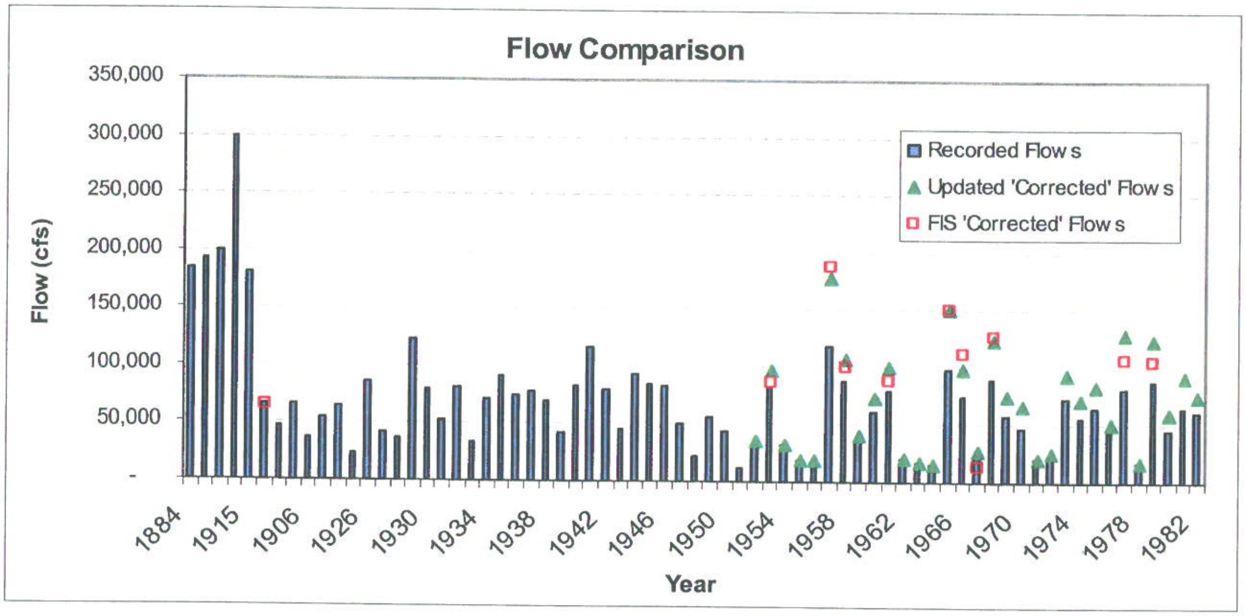


Figure 5-1

When all of the measured discharges between 1952 and 1982 were adjusted according to the method described in Section 4.3, the LPIII analysis using the same historical data and period of record as was used for the FIS resulted in a 1 percent exceedance discharge of 239,000 cfs. As indicated in Section 1.5.1, only nine of the 30 flows occurring between 1953 and 1982 were adjusted for the EHA study. Although the EHA Study states “those affected by flood storage were adjusted to natural conditions“, it is not entirely clear what criteria was used in determining the lower limit, below which flows were not adjusted. However, since not all of the measured discharges were adjusted to reflect the reservoirs in the EHA study, a second flood flow frequency analysis was performed using adjusted peaks discharges for the same years as the FIS. The resulting 1-percent annual chance discharge for the second analysis is 240,000 cfs. Since both analyses replicated the EHA discharge within one percent, the simplified method of adjusting the measured discharges was deemed to be consistent with the original FIS method.

This analysis adjusted all the annual peak discharges occurring between 1952 and 2004.

5.5 Results

The unregulated data set used for the Brazos River flood frequency analysis is shown in Table 5.3.

Table 5.3
Brazos River Flood Frequency Analysis
Flow Data

	Year	Recorded Annual Peak Flow (cfs)	Regulated to Unregulated Ratio	Reservoir Adjustment	Final Adjustment Ratio	Unregulated Flow for FFA (cfs)
Historical Data	1884	184,000	1.0	NA	1.0	184,000
	1885	193,000	1.0	NA	1.0	193,000
	1899	200,000	1.0	NA	1.0	200,000
	1913	300,000	1.0	NA	1.0	300,000
	1915	181,000	1.0	NA	1.0	181,000
Unregulated Period	1903	66,600	1.0	NA	1.0	66,600
	1904	47,600	1.0	NA	1.0	47,600
	1905	65,600	1.0	NA	1.0	65,600
	1906	37,300	1.0	NA	1.0	37,300
	1923	54,900	1.0	NA	1.0	54,900
	1924	64,800	1.0	NA	1.0	64,800
	1925	24,200	1.0	NA	1.0	24,200
	1926	86,900	1.0	NA	1.0	86,900
	1927	42,500	1.0	NA	1.0	42,500
	1928	36,800	1.0	NA	1.0	36,800
	1929	123,000	1.0	NA	1.0	123,000
	1930	78,800	1.0	NA	1.0	78,800
	1931	52,100	1.0	NA	1.0	52,100
	1932	80,500	1.0	NA	1.0	80,500
	1933	34,000	1.0	NA	1.0	34,000
	1934	71,400	1.0	NA	1.0	71,400
	1935	90,900	1.0	NA	1.0	90,900
	1936	74,700	1.0	NA	1.0	74,700
	1937	77,100	1.0	NA	1.0	77,100
	1938	68,600	1.0	NA	1.0	68,600
	1939	41,900	1.0	NA	1.0	41,900
	1940	82,100	1.0	NA	1.0	82,100
	1941	117,000	1.0	NA	1.0	117,000
	1942	79,400	1.0	NA	1.0	79,400
	1943	45,500	1.0	NA	1.0	45,500
	1944	93,800	1.0	NA	1.0	93,800
	1945	85,000	1.0	NA	1.0	85,000
	1946	82,500	1.0	NA	1.0	82,500
	1947	51,000	1.0	NA	1.0	51,000
	1948	22,100	1.0	NA	1.0	22,100
	1949	56,000	1.0	NA	1.0	56,000
	1950	44,500	1.0	NA	1.0	44,500
	1951	11,100	1.0	NA	1.0	11,100

Table 5.3
Brazos River Flood Frequency Analysis
Flow Data

	Year	Recorded Annual Peak Flow (cfs)	Regulated to Unregulated Ratio	Reservoir Adjustment	Final Adjustment Ratio	Unregulated Flow for FFA (cfs)
Partially Regulated Data	1952	34,700	1.024	0.38	1.009	34,700
	1953	96,500	1.425	0.38	1.162	96,500
	1954	32,400	0.940	0.38	0.977	32,400
	1955	19,300	0.955	0.55	0.975	19,300
	1956	17,900	0.950	0.55	0.973	17,900
	1957	177,000	1.886	0.55	1.487	177,000
	1958	107,300	1.408	0.55	1.225	107,300
	1959	41,100	1.088	0.55	1.048	41,100
	1960	73,200	1.388	0.55	1.213	73,200
	1961	99,600	1.480	0.55	1.264	99,600
	1962	21,000	1.037	0.55	1.020	21,000
	1963	17,400	0.919	0.63	0.949	17,400
	1964	14,400	0.804	0.63	0.876	14,400
	1965	150,300	1.723	0.72	1.521	150,300
	1966	98,700	1.454	0.72	1.327	98,700
	1967	27,300	1.061	0.81	1.049	27,300
	1968	124,100	1.423	0.91	1.385	124,100
	1969	74,400	1.308	0.91	1.280	74,400
	1970	66,600	1.431	0.91	1.392	66,600
	1971	20,100	0.901	0.91	0.910	20,100
	1972	24,900	1.024	0.91	1.022	24,900
	1973	93,300	1.315	0.91	1.286	93,300
	1974	71,100	1.313	0.91	1.285	71,100
	1975	82,800	1.323	0.91	1.294	82,800
	1976	50,800	1.162	0.91	1.147	50,800
	1977	129,200	1.644	0.94	1.605	129,200
	1978	16,100	0.752	0.94	0.767	16,100
	1979	123,200	1.423	0.94	1.398	123,200
	1980	58,900	1.301	0.98	1.295	58,900
	1981	91,500	1.423	0.98	1.415	91,500
	1982	74,700	1.222	0.98	1.218	74,700
Fully Regulated Data	1983	74,600	1.273	1.0	1.273	74,600
	1984	10,600	0.821	1.0	0.821	10,600
	1985	43,100	1.185	1.0	1.185	43,100
	1986	60,300	1.322	1.0	1.322	60,300
	1987	99,100	1.462	1.0	1.462	99,100
	1988	17,100	0.774	1.0	0.774	17,100
	1989	55,000	1.255	1.0	1.255	55,000
	1990	83,800	1.501	1.0	1.501	83,800
	1991	67,200	1.307	1.0	1.307	67,200
	1992	164,200	1.747	1.0	1.747	164,200
	1993	82,100	1.366	1.0	1.366	82,100
	1994	42,000	1.235	1.0	1.235	42,000

Table 5.3 Brazos River Flood Frequency Analysis Flow Data						
	Year	Recorded Annual Peak Flow (cfs)	Regulated to Unregulated Ratio	Reservoir Adjustment	Final Adjustment Ratio	Unregulated Flow for FFA (cfs)
	1995	130,700	1.483	1.0	1.483	130,700
	1996	24,700	0.859	1.0	0.859	24,700
	1997	94,300	1.541	1.0	1.541	94,300
	1998	72,500	1.368	1.0	1.368	72,500
	1999	113,400	1.412	1.0	1.412	113,400
	2000	14,600	0.773	1.0	0.773	14,600
	2001	65,000	1.392	1.0	1.392	65,000
	2002	64,600	1.235	1.0	1.235	64,600
	2003	93,600	1.252	1.0	1.252	93,600
	2004	97,000	1.420	1.0	1.420	97,000

The data set used for the flood frequency analysis is based on the observed unregulated data including the historic peaks and systematic record up to 1951, observed data from 1952 to 1982 adjusted for partial regulation if the computed adjustment was greater than 1.0, and the observed regulated data from 1982 to 2004 adjusted to an unregulated condition, if the computed adjustment was greater than 1.0.

The results of the Brazos River flood frequency analysis are shown in Table 5.4.

Table 5.4 Brazos River at Richmond Computed Probability Curve		
Probability	Return Interval	Flow (cfs)
0.9999	1	8,970
0.5	2	62,700
0.2	5	106,000
0.1	10	134,000
0.05	20	160,000
0.02	50	192,000
0.01	100	215,000
0.005	200	237,000
0.002	500	264,000

5.6 Reliability

After determining the flood frequency at a gage location, additional issues need to be considered. Gage measurements can be deficient or biased, and the flow data that has been estimated from these measurements has inherent errors that are introduced to the flood frequency analysis. Confidence limits can be used to evaluate the uncertainties inherent in the frequency determination by providing either a measure of the uncertainty of the estimated exceedance probability of a selected discharge, or the measure of the uncertainty of the discharge at a selected exceedance probability.

The .05 and .95 confidence limits generated by the log-Pearson III analysis are shown below.

Table 5.5
Brazos River at Richmond
Confidence Limits

Percent Chance Exceedance	Computed Flow (cfs)	Confidence Limits (cfs)	
		0.05	0.95
FIS			
0.2	316000	442000	244000
0.5	271000	370000	213000
1	238000	318000	189000
2	205000	269000	166000
5	163000	207000	134000
10	131000	162000	110000
20	100000	120000	85800
50	57600	66600	50000
80	31500	36800	26400
90	22600	26900	18200
95	16900	20700	13100
99	9620	12500	6860
With Simplified Adjustment			
0.2	308,000	425,000	240,000
0.5	269,000	363,000	213,000
1	239,000	317,000	191,000
2	209,000	272,000	169,000
5	169,000	213,000	140,000
10	138,000	170,000	116,000
20	107,000	128,000	91,300
50	62,000	71,600	53,800
80	33,800	39,400	28,300
90	24,000	28,600	19,300
95	17,800	21,800	13,800
99	9,820	1,2800	6,960
With Simplified Adjustment and Station Skew			
0.2	308,000	425,000	240,000
0.5	269,000	363,000	213,000
1	239,000	317,000	191,000
2	209,000	272,000	169,000
5	169,000	213,000	140,000
10	138,000	170,000	116,000
20	107,000	128,000	91,300
50	62,000	71,600	53,800
80	33,800	39,400	28,300
90	24,000	28,600	19,300
95	17,800	21,800	13,800
99	9,820	1,2800	6,960

Table 5.5
Brazos River at Richmond
Confidence Limits

Percent Chance Exceedance	Computed Flow (cfs)	Confidence Limits (cfs)	
		0.05	0.95
With Simplified Adjustment, Station Skew and 22 Years Additional Gage Data			
0.2	264000	340000	215000
0.5	237000	301000	195000
1	215000	270000	179000
2	192000	239000	161000
5	160000	194000	136000
10	134000	160000	115000
20	106000	123000	92300
50	62700	71000	55500
80	33900	38700	29200
90	23600	27600	19700
95	17200	20600	13800
99	8970	11400	6640

As more data becomes available the flood frequency estimate will generally improve and the confidence limits will narrow.

5.7 Regulated Condition Discharge

To use the Brazos River flood flow frequency curve for the Richmond gage to determine the one-percent annual chance flood hazard area, the discharges computed for homogeneous/unregulated conditions must be changed to regulated conditions. For the FIS, the EHA study created a rainfall-runoff model of the natural Brazos River basin below Possum Kingdom Dam using the USACE HEC-1 computer program. The model was "calibrated" to produce a 100-year flow of 238,000 cfs to match the results of the flood frequency analysis.

EHA then added the eight reservoirs (Whitney, Waco, Proctor, Belton, Georgetown, Granger, Stillhouse Hollow, and Somerville) to the HEC-1 model and routed the flows through each of the reservoirs using the modified Puls method. The initial stage for each reservoir was set at the top of the conservation pool and only spillway flows at stages above the top of the flood control pools were modeled. The results of the EHA HEC-1 model indicated the peak flows for the regulated conditions, which were then used for the FIS.

The procedure of 1) creating a rainfall-runoff model, 2) calibrating to generate the flow that agrees with the flood frequency analysis, and 3) then adding the reservoirs to generate the regulated discharge at the Richmond gage is the method by which the regulated discharge would be determined for this analysis. It was decided, therefore, to use the ratio of regulated to unregulated discharge that was developed for the FIS for this analysis, also. The resulting regulated discharges are shown below.

Table 5.6
Brazos River at Richmond
Updated FIS Flow Distribution

Probability	Return Interval	FIS Unregulated	FIS Regulated	Ratio	Updated Unregulated	Updated Regulated[1]
0.1	10	131,000	101,000	0.771	134,000	103,000
0.02	50	205,000	157,000	0.766	192,000	147,000
0.01	100	238,000	181,000	0.761	215,000	164,000
0.002	500	316,000	242,000	0.766	264,000	202,000

[1] Adjusted using the same ratio as the effective FIS discharges.

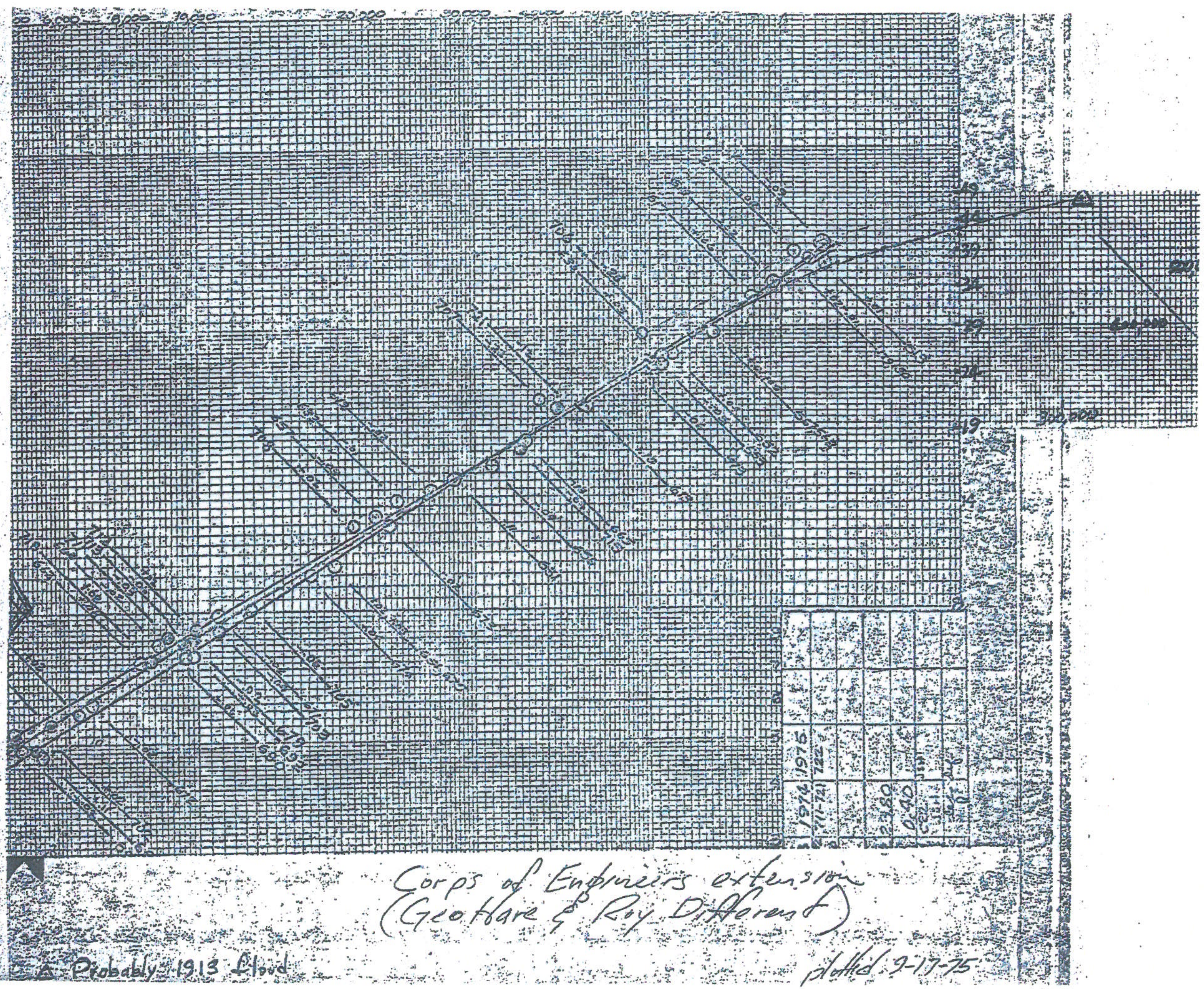
5.8 Summary

A simplified method was used to determine the adjustment for USGS flow data for the Brazos River at Richmond from regulated to unregulated conditions. Based on graphical analysis comparing trendlines of the pre-reservoir data from 1903 to 1951 with the regulated data from 1983 to 2004 adjustment factors were established for each discharge. Additional conversions were used for the discharges occurring during the transition period, from 1951 to 1982, when the reservoirs were being constructed. .

Following the recommendations of Bulletin 17-B, probability distributions for the unregulated flows for the Brazos River at Richmond were determined using various combinations of systematic and historical flood data, including the original flow frequency data used for the 1987 FIS. The results from the analysis replicating the EHA study using the unregulated discharges developed for the current analysis matched the results of the 1987 study within 0.4 percent. It was, therefore, concluded that the simplified method use to adjust measured discharges for the Brazos River at the Richmond gage followed closely with the procedure used to adjust the discharges for the 1987 FIS, and that the method was valid and can be used in the future as additional measured data is obtained.

After the flood frequency curve for unregulated conditions was developed, the regulated flood frequency curve was determined using relationship between the regulated and unregulated discharges that was developed for the 1987 FIS. Based on the current analysis, the Brazos River 100-year discharge at the Richmond gage is approximately 164,000 cfs.

APPENDIX A
SUPPLEMENTARY DOCUMENTATION



20,000
30,000
300,000
1974 1976
Corps of Engineers extension
(Geo Hare & Roy Differenf)
△ Probably 1913 flood
plotted 9-17-75

Copied 10-10-06 by SWT

9-276
(Rev. 7-67)

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES DIVISION

Station Number

LEVEL NOTES

Stream Brazos River at Richmond Tex

Locality Obj: Highwater Marks 1913 and 1929

Party Rupp & Tipper Date Aug 24, 1931

STATION	B. S.	HT. INST.	F. S.	ELEVATION	REMARKS
	0.00	41.77		41.77	Direct on OG
			+3.61	45.38	Top of timber nailed to Cottonwood 75' downstream from present highway bridge and is 1913 Flood
			left bank		
	Highwater marks for			1913	Flood
BM2	3.58			~~41.41~~ ~~47.00~~	
		~~[illegible]~~	5.75	39.71	HW mark for 1929 Flood about 500 ft to left and 200' downstream. This mark is floor of a cabin in Tourist camp on left bank
TP1	7.26	51.69	1.15	44.43	
			4.60	47.09	End of Point of land in Blaisdells yard that was at waters edge in peak of 1913 flood 800 feet left and 75' US from gage (unreliable)
TP 2	3.54	46.37	8.86	42.83	
			6.58	39.79	HW 1929'
TP 3	4.42	45.72	5.07	41.21 ~~41.36~~	
BM2			3.75	41.80 ~~41.97~~	

No.____of____sheets________Comp. by____________Chk. by____________

GPO : 1980 O - 320-040

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
Austin 14, Texas

October 27, 1944

Mr. W. H. Goines
Houston 14, Texas.

Brazos River at Richmond, Tex.

Information in this office concerning the elevation of the 1913 flood at Richmond indicates that the figure of 45.4 ft. which has been published since the establishment of the station, is 2 feet or more too low. This elevation was determined by levels of Aug. 24, 1931, by determining the elevation of the top of a piece of timber nailed to a cottonwood tree located on left bank 75 feet downstream ffom highway bridge said to mark the 1913 flood.

In order that we may have the best information now available concerning the elevation of the 1913 flood, it would be well for you to try to find additional floodmarks in the vicinity of Richmond, preferably below the railroad and near the gage. It would be well also to tie in the base of rail at the railroad bridge to gage datum and to find out from the railroad company if any changes in the elevation of the base of rail have been made.

Please do this at your first convenient opportunity.

C. E. Ellsworth
District Engineer

FORM A-7

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES BRANCH

File No.

Washington

RECORDED

LEVEL NOTES

Field

Station Brazos River at Richmond, Tex.

Date Feb. 1, 19 45 Level No. W.R. 169

Party Goines and Blackburn

Purpose of levels To verify Dec. 1913 flood data.

Chain length found ... ft. at ... m

Chain length changed to ... ft. at ... m

Given length ... ft. Corr. length from levels ... ft.

Given check-bar elevation, by gage dial ... ft.

Check-bar elevation found, by gage dial ... ft. at ... m

Given check-bar elevation, by previous levels ... ft.

Check-bar elevation found, by these levels ... ft

Check-bar elev. (by dial) corrected on basis of these levels to ... ft. at ... m

SUMMARY OF RESULTS OF LEVELS

Object	Elev. Given	Elev. From Levels	G. Ht. Corr.
U.S.G.S. B.M. 1930	[illegible]	base	
Dec. 1913 flood [illegible]		* 48.3 See	[illegible]
do		* 47.8 [illegible]	
do		* 48.1	
U.S.G.S. B.M. 1930		[illegible]	0.005 error
			[illegible]
* No [illegible]	[illegible] to	[illegible] to	[illegible]
[illegible]			
[illegible]	[illegible]	[illegible]	[illegible]
at [illegible]	[illegible]	upstream	5121

Remarks [illegible] are [illegible] those of Jan. 9, 1945

[illegible] 48.0 [illegible] than 47.5 (from [illegible]) as there [illegible] [illegible] [illegible]

Sheet 1 of 4 sheets.

G1323-740-2m

9-275 d
(Sept., 1927)

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES BRANCH

No. of Meas.

Date Feb. 1. 1945

SUPPLEMENTARY DISCHARGE MEASUREMENT NOTES

Brazos River at Richmond, Tex.

Enter on this form ample notes in regard to the following:

1. Accuracy of measurement; 2, gage; 3, observer; 4, bench marks; 5, gage-height corrections; 6, adjustments to total discharge; 7, station equipment; 8, channel, control, and point of zero flow; 9, rating, backwater; 10, diversions, regulation; 11, records; 12, cooperation.

Mr. S. J. Butler, USWB river observer and City of Richmond Water Supt., found high water marks for 1913 flood, these marks are upstr. from R.R. Mr. Butler said that R.R. dump had been raised since 1913 and at time of flood, the RR dump had no effect on water surface el.

Mark in blacksmith shop: a scratched mark inside of shop, identified to Mr. Butler by A. Kochan, who owned shop in 1913. Elev. 48.3' There is a vise outside of shop, which Mr. Kochan said was just under water, Elev. 47.8' the blacksmith shop is 0.1 mile to right of river and about 100 ft upstr. from R.R. or about 1,000 ft. upstr. from recorder.

Mark at lumber yard: Mark on porch of lumber yard office, identified to Mr. Butler by J.A. Wessendorff, who was a bookkeeper at lumber yard in 1913 and is now owner. Peak 48.1', Mr. Wessendorff said that river peaked at this point and then ~~fell~~ to a point

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No. 3 of 4 sheets

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…ept., 1927)

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES BRANCH

No. of Meas. ____________

Date Feb. 1, 19 45

SUPPLEMENTARY DISCHARGE MEASUREMENT NOTES

Brazos River at Richmond, Tex.

Enter on this form ample notes in regard to the following:

1. Accuracy of measurement; 2, gage; 3, observer; 4, bench marks; 5, gage-height corrections; 6, adjustments to total discharge; 7, station equipment; 8, channel, control, and point of zero flow; 9, rating, backwater; 10, diversions, regulation; 11, records; 12, cooperation.

at Elev. 47.9' and held this stage for about
two weeks, then began to fall continuously.
The lumber yard is 0.35 mile to right of river
and about 200 ft upstr. from RR or about ~~1,000~~ 1,100
ft upstr. from recorder.
Neither of these buildings have been
altered since 1913. Water surface was not
affected by RR dump. There is a small creek
about 0.1 mile upstream from RR which runs
more or less parallel to RR so that water in
over flow area should be about the same elev.
as water in main channel.
These high water marks are about the
same as those determined by levels of 1/9/45
i.e. 47.5' and 47.7'.

HG
2/1/45

G—C226 U. S. GOVERNMENT PRINTING OFFICE

No. 4 of 4 sheets

FORM A-7

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES BRANCH

File No. ______
Washington ______
Field ______

RECORDED

LEVEL NOTES

Station Brazos River at Richmond Tex.

Date Jan 9, 1945 Level No. W.R. 169

Party Gaines and Longacre

Purpose of levels To tie historic flood crests to U.S.G.S. gage datum. Stadia dist. between recorder (Highway br.) and R.R. bridge. To tie gage datum to m.s.l. datum.

Chain length found ______ ft. at ______ m

Chain length changed to – ______ ft. at ______ m

Given length – ______ ft. Corr. length from levels ______ ft.

Given check-bar elevation, by gage dial – ______ ft.

Check-bar elevation found, by gage dial – ______ ft. at ______ m

Given check-bar elevation, by previous levels – ______ ft.

Check-bar elevation found, by these levels – ______ ft

Check-bar elev. (by dial) corrected on basis of these levels to – ______ ft. at ______ m

SUMMARY OF RESULTS OF LEVELS

Object	Elev. Given	Elev. From Levels	G. Ht. Corr.
May 1882	43.7 ft.	From S.P. R.R. Co. at R.R. bridge 925 ft. upstr. from recorder *slope correction not applied.	
June 13, 1885	44.7		
July 1899	45.6		
Dec. 1913	47.5		
May 2, 1915	43.3		
May 9, 1922	43.9		
June 5, 1929	40.6	from floodmarks by U.S.G.S. Engrs. at recorder site.	
* No slope data available, estimate slope corr.			-0.2 ft.
Base of rail		52.6 Rec. datum	
U.S.G.S. B.M. H3 1930 located on toe of downstr end of right pier of R.R. bridge	Elev. 46.495 ft. above zero of gage.		

Remarks Stadia distance from R.R. bridge to recorder 925 ft. This has been published as "about 1500 ft".

See levels of Oct. 13, 1944, which are superseded by these levels.

Sheet 1 of 5 sheets.

G1323-740-2m

See levels of Feb. 1, 1945

USGS H1 1930

File No.

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES BRANCH

May 1922

Washington

Field

LEVEL NOTES

Stream Brazos River at Richmond, Tex.

Purpose To tie R.R. datum to recorder datum.

Date 1-9-45 19

Party W.H.G. & J.K.L.

STATION	B. S.	HT. INST.	F. S.	ELEVATION	REMARKS
B.M. 6	7.170	58.445		51.275	
T.P.	3.100	55.375	6.170	52.275	
T.P.	3.650	55.845	2.180	52.195	
T.P.	6.455	55.585	6.780 (15)	49.130	
U.S.G.S. H1 1930			9.090	46.495	
S/R			3.000	52.[illegible]	St. end bridge
T/R			2.550	53.035	do
S/R			3.050	52.535	[illegible]
T/R			2.600	52.985	do
T.P.	[illegible]	[illegible]	6.565	[illegible]	[illegible]
T.P.	2.100	55.[illegible]	4.795	51.[illegible]	[illegible]
T.P.	6.940	[illegible] 4	3.550	[illegible]	[illegible]
B.M. 6			7.670	51.2(7)0	0.005 error of closure

Dist. from RR bridge to recorder 925 ft by stadia

Base of rail = 95.3 R.R. datum
Base of rail (B/R) = 52.6 U.S.G.S. recorder datum
42.7 ft difference.

No. 2 of 5 sheets. Comp. by W.H.G. Chk. by SDR

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9-275 d
(Sept., 1927)

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES BRANCH

Date 1-9-45, 19___ No. of Meas.___

SUPPLEMENTARY DISCHARGE MEASUREMENT NOTES

Brazos River at Richmond, Tex.

Enter on this form ample notes in regard to the following:

1. Accuracy of measurement; 2, gage; 3, observer; 4, bench marks; 5, gage-height corrections; 6, adjustments to total discharge; 7, station equipment; 8, channel, control, and point of zero flow; 9, rating, backwater; 10, diversions, regulation; 11, records; 12, cooperation.

The following was obtained from Engineers office of S.P.R.R.

From profiles of R.R bridge flood crests were plotted to R.R. datum as:

Dec. 1913	90.2 or	47.5	U.S.G.S. recorder datum see sheet 2
July ~~June~~ 1899	88.3	45.6	
June 13, 1885	87.4	44.7	
May 1884	86.4	43.7	
May 2, 1915	86.0	43.3	
May 9, 1922	83.6	40.9	
June 6, 1929	82.9	40.2	
May 17, 1930	70.4	27.7	
Base of rail	95.3	52.6	
Top of rail	95.8	level bridge	

From other records in S.P.R.R. Engr's office (basis for plotting some of the above):

			recorder datum
Dec. 1913 Crest	5.1 ft. below B/R.		47.5
June 1899	7'-6½"	✓	45.1
May 1922	12.7 ft	✓	39.9
June 1929	12.4 or 12.6	✓	40.2 or 40.0
May 27, 1935	16.2	✓	36.4

9-275 d
(Sept., 1927)

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES BRANCH

No. of Meas. ______

Date 1-9-45, 19__

SUPPLEMENTARY DISCHARGE MEASUREMENT NOTES

Brazos River at Richmond, Tex.

Enter on this form ample notes in regard to the following:

1. Accuracy of measurement; 2, gage; 3, observer; 4, bench marks; 5, gage-height corrections; 6, adjustments to total discharge; 7, station equipment; 8, channel, control, and point of zero flow; 9, rating, backwater; 10, diversions, regulation; 11, records; 12, cooperation.

recorder datum
Oct 1, 1936 20.6 (crest 2pm) below B/R. 32.0

Summary of flood data to recorder datum.

Dec. 1913 highest known flood, information dating back to 1884 (first flood recorded by R.R.). From R.R. Co crest was 47.5 ft. Mr. S. J. Butler, U.S.W.B. observer, said that crest held for about 36 hours and that waves touched lower chord of center span of R.R. bridge, he thought that elev. of bottom of lower chord would give crest within .5 ft. (L.C. is 4.8' below B/R, 52.5 - 4.8 = 47.7 ft.) or 47.7 ± 0.5 ft. This is a good verification of R.R. data, use 47.5

June 1899 R.R. is conflicting, from profile, crest was 45.6, from notes 45.1, other notes show that bridge was raised 1.9 ft. about 1905. Since elevations shown on sheet 3 were from a profile dated subsequent to 1905 it has been assumed that all corrections and adjustments had been made to agree with present

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No. 4 of 5 sheets

9-275 d
(Sept., 1927)

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES BRANCH

Date 1-9-45, 19___ No. of Meas.______

SUPPLEMENTARY DISCHARGE MEASUREMENT NOTES

Brazos River at Richmond, Tex.

Enter on this form ample notes in regard to the following:

1. Accuracy of measurement; 2, gage; 3, observer; 4, bench marks; 5, gage-height corrections; 6, adjustments to total discharge; 7, station equipment; 8, channel, control, and point of zero flow; 9, rating, backwater; 10, diversions, regulation; 11, records; 12, cooperation.

bridge Use 45.6

June 13, 1885 44.7

May 1884 43.7

May 2 1915 43.3

May 9 1922 42.9

* June 6 1929 40.2 published by U.S.G.S. as 40.6

* May 27 1935 36.4 from U.S.G.S recorder 36.12

* These show close agreement, use U.S.G.S. data.

No. 5 of 5 sheets 6—6220 U. S. GOVERNMENT PRINTING OFFICE

InterOffice Memorandum

Baker

To:	Andrew Cao	Date:	November 1, 2006 (revised 12/26/06, 02/23/2007, 06/2007, 07/2008)
From:	Dong Nguyen	Subject:	Fort Bend County DFIRM project Brazos River Peak Flow Attenuation Analysis

Objective

The effective Brazos River study (by Espey Huston Associates (EHA), 1985) has determined the 100-year Flow at Richmond at 181,000 cfs. This flow was assumed to stay unchanged for the entire 87 miles of river within Fort Bend County. Due to this long distance, some attenuation of the peak flow should occur. This memo summarizes the analysis of the attenuation of the Brazos River peak flows between the gaging stations of Hempstead, Richmond, and Rosharon using published data from the United States Geological Survey (USGS). Based on this analysis, flow distribution table for the Brazos River within Fort Bend County is defined.

Attenuation Analysis Between Hempstead, Richmond, and Rosharon Gaging Stations

Peak Flow Data

Annual peak flow data from four USGS gages at Hempstead (#08111500), Richmond (#08114000), Rosharon (#08116650), and Mill Creek (#08111700) from 1939 to 2004 were used for this analysis (see **Figure 1**). Mill Creek is a tributary to the Brazos River downstream of Hempstead. The annual peak flow data indicates that there are peak flow reductions from Hempstead to Richmond and from Richmond to Rosharon. For this analysis, only high flooding events defined as having the Hempstead peak flows about or higher than 80,000 cfs are considered. **Table 1** shows the comparisons of the annual peak flows between the Hempstead, Richmond, and Rosharon gages. Ratios between each gaging stations peak flows are also provided.

TABLE 1: COMPARISONS OF ANNUAL BRAZOS RIVER PEAK FLOWS BETWEEN HEMPSTEAD, RICHMOND, ROSHARON GAGES
All flow values are in cfs and are sorted by Peak Flows at Hempstead

Date	Mill Creek	Date	Hempstead (H)	Date	Richmond (R)	R/H	Date	Rosharon (Ro)	Ro/R
		1998	79,000						
		07/03/40	83,100	07/04/40	82,100	1.0			
6/7/79	35,500	06/07/79	83,800	06/08/79	88,100	1.1	6/9/79	76,500	0.9
11/28/04	10,700	11/27/04	84,100	11/29/04	76,700	0.9	11/29/04	71,100	0.9
		04/20/77	84,700	04/22/77	80,500	1.0	4/23/77	73,000	0.9
		05/20/46	85,300	05/20/46	82,500	1.0			
		04/29/42	90,500	05/01/42	79,400	0.9			
		05/22/65	106,000	05/25/65	98,800	0.9			
		04/26/45	106,000	04/27/45	85,000	0.8			
		05/07/44	108,000	05/08/44	93,800	0.9			
		10/17/94	109,000	10/21/94	88,100	0.8	10/22/94	84,400	1.0

		12/28/91	116,000	01/01/92	94,000	0.8	1/3/92	82,700	0.9
		11/30/40	116,000	11/28/40	117,000	1.0			
		05/02/57	143,000	05/05/57	119,000	0.8			

The table above indicates that the reduction of peak flows is about 10% to 20% between the Hempstead and Richmond gages and about 10% between the Richmond and Rosharon gages. The reduction is higher with higher flows. If the Mill Creek is significant, it will reduce the flow reduction factor between Hempstead and Richmond and sometimes will push the Richmond flow above the Hempstead flow.

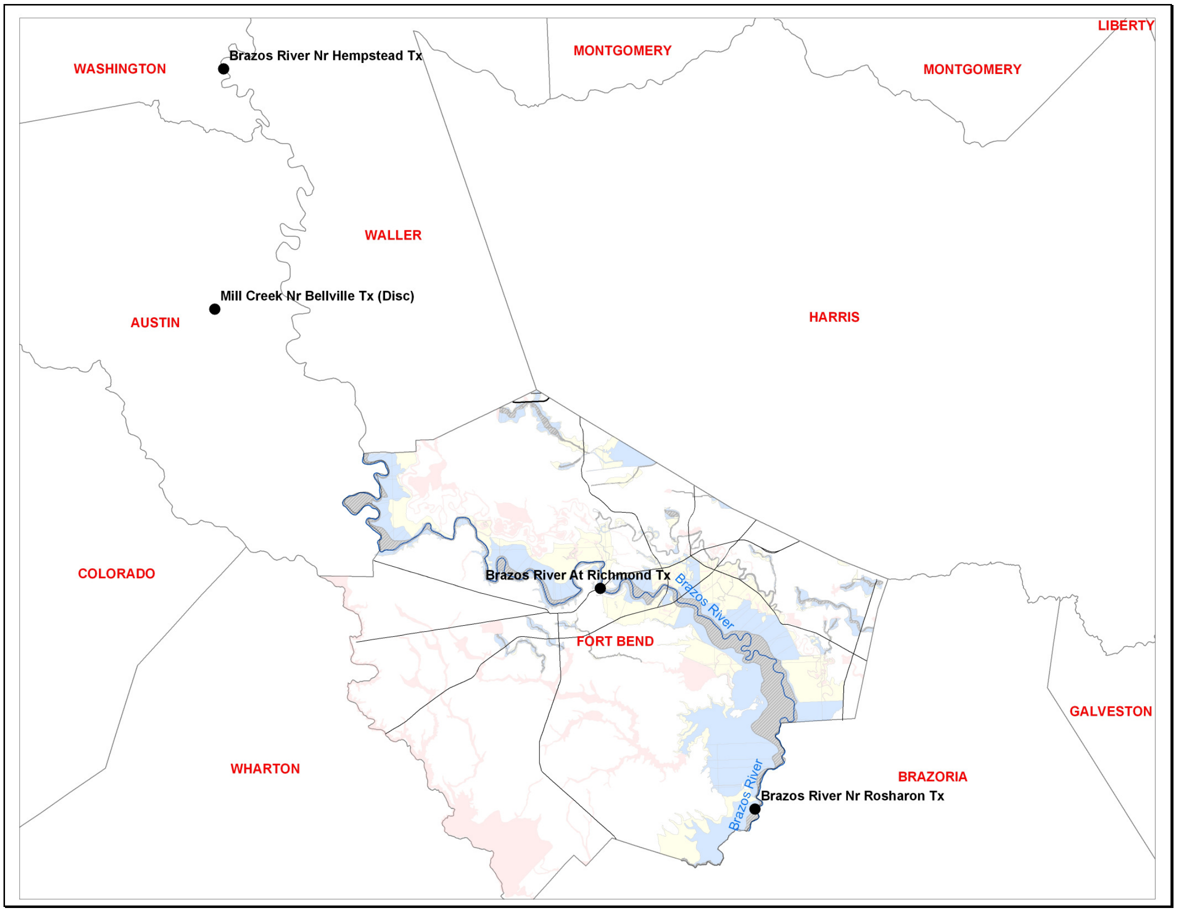

Figure 1: Locations of USGS Gaging Stations

<u>Flow Hydrographs</u>

To better define the attenuation of the Brazos River peak flows shown on Table 1, flow hydrographs from the 1991, 1994 and 1998 events, available from the USGS Woodlands office, were used. **Figures 2, 3** and **4** show flow hydrographs at Hempstead, Richmond, Mill Creek, and Rosharon gages during these events.

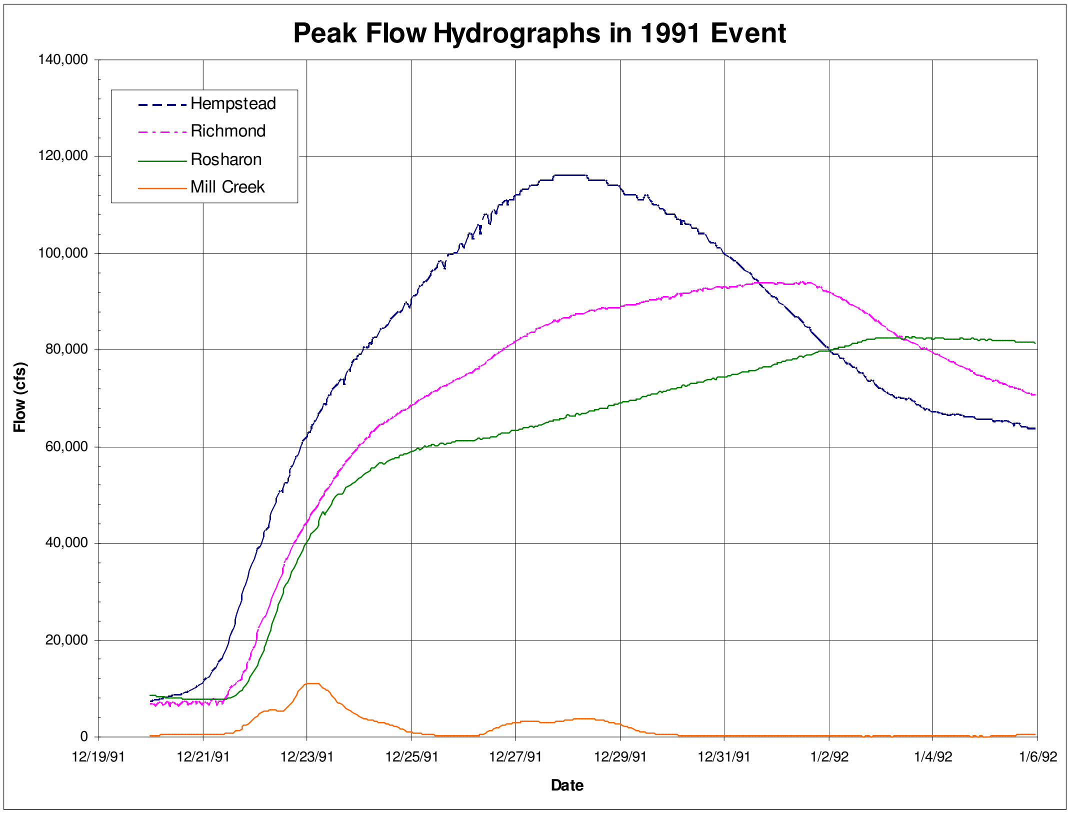

Figure 2: Flow Hydrographs during the December 1991 Event

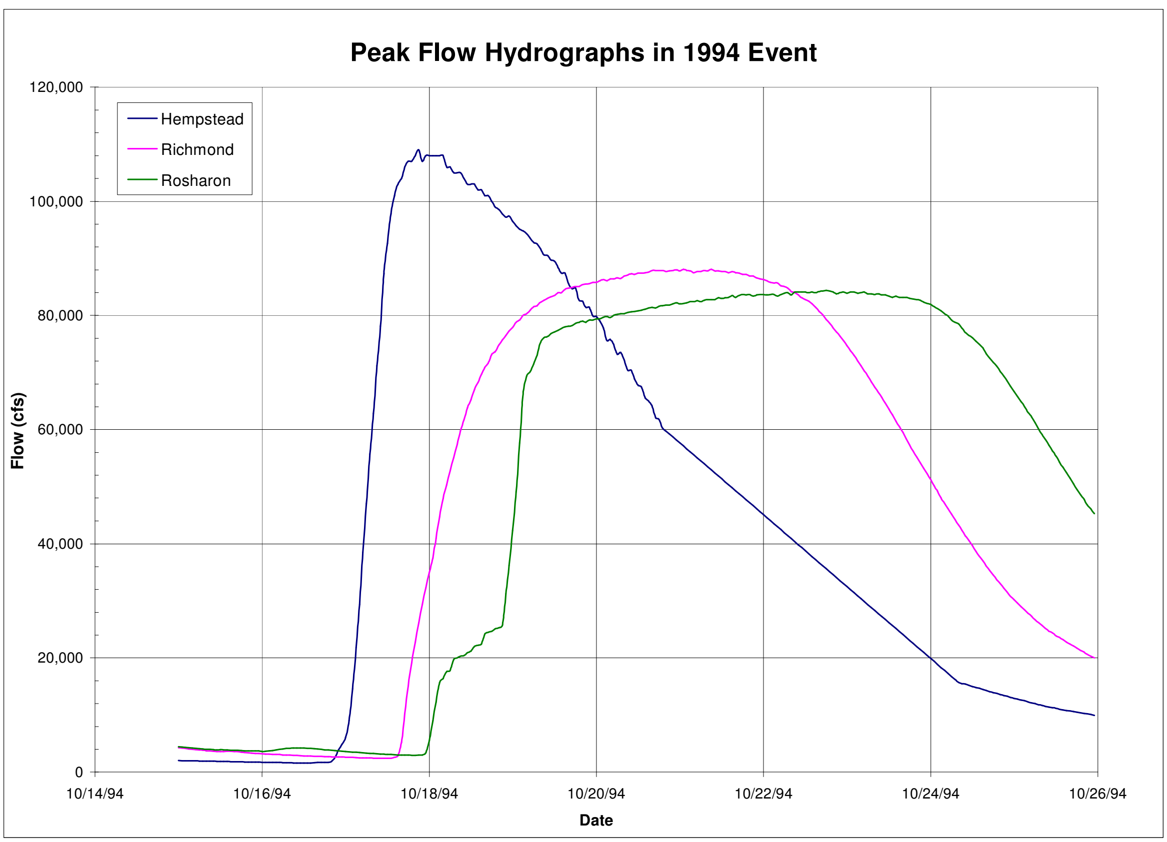

Figure 3: Flow Hydrographs during the October 1994 Event

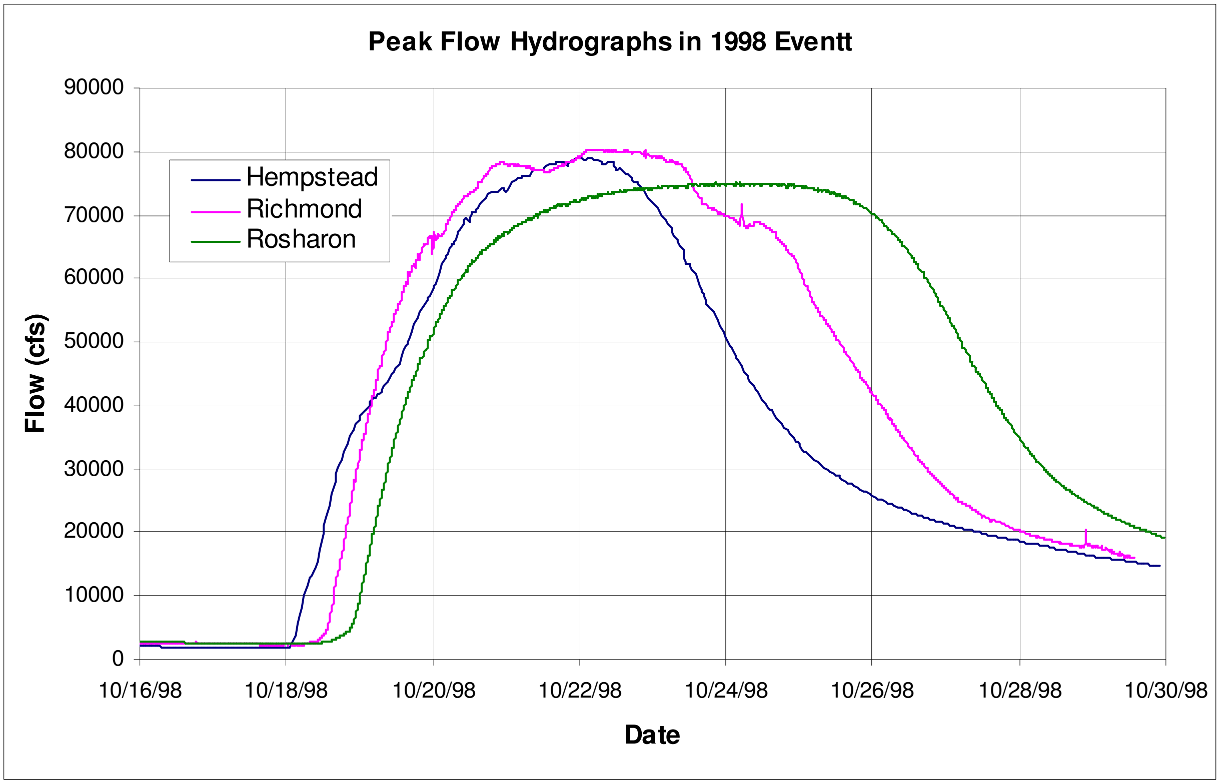

Figure 4: Flow Hydrographs during the October 1998 Event

The 1998 flow hydrographs show that there was no attenuation between the Hempstead and Richmond gages. The Richmond peak flow of 80,300 cfs was slightly higher than the Hempstead peak flow of 79,000 cfs. It was assumed that there were additional flows coming from Mill Creek, which pushed the Richmond flow higher. Therefore, the 1998 event was not used in this analysis.

The 1991 and 1994 flow hydrographs indicated peak flow attenuation between the Hempstead, Richmond, and Rosharon gages. The 1991 flooding event resulted from several days of heavy rainfall in South Central and Southeast Texas ("Floods in central Texas, December 1991", Hejl HR et al, USGS). By comparison, the 1994 event resulted from fewer days of intense rainfall in Southeast Texas ("Floods in Southeast Texas, October 1994", Fred Liskum and Jeffery East, USGS). Due to more intense rainfall within a smaller area, the rising limb of the 1994 Hempstead hydrograph was steeper than the 1991 hydrograph. The 1991 hydrographs are probably more descriptive of a typical 100-year flooding situation, when most of the Brazos River lower watershed contributes to the runoff, and are therefore used as the basis for our flow attenuation analysis. The 1994 event was used for comparison since the relatively localized runoff condition would limit its applicability. The 1994 hydrographs at Richmond and Rosharon also indicated strong backwater situations. In both events, the peak flows between Hempstead and Richmond are attenuated similarly although the hydrograph shapes are different. The flow drop between Richmond and Rosharon is much more pronounced during the 1991 event. This might be due to either a higher backwater in the 1994 event, or the overflow condition upstream of Rosharon that occurred with the higher 1991 flow.

Attenuation Analysis using HEC-RAS Unsteady Flow option

The unsteady flow option of HEC-RAS was used as the main tool to calculate the flow distributions of different flow events from the Waller/Fort Bend County line to Brazoria/Fort Bend County line. As mentioned above, the 1991 hydrograph was used as the basis for the flow distribution calculations of the calibration and multi-event flows (10-, 2-, 1-, 0.2-percent storm events) analyses. For the flow distribution of 1991 storm, the Hempstead flow hydrograph is reduced by an attenuation factor and was routed from the Waller/Fort Bend county line to Rosharon Gage (FM 1462). The attenuation factor is adjusted until the Richmond computed flow is equal to the measured value of 94,000 cfs. Similarly, for the flow distribution of 1% storm, the Hempstead flow hydrograph is increased by an attenuation factor and was routed from the Waller/Fort Bend county line to the confluence of the Cow Creek and Brazos River location. The attenuation factor is adjusted until the Richmond computed flow is equal to the proposed value of 164,000 cfs

The computed flow distribution along the Brazos River is similar to the 100-year hydrograph calculation shown on Figure 5 and 6. The resulting flow curve does look appropriate with sharp drops upstream and downstream along large flood plain areas as expected. Along the central part of the river, where the flood plain is smaller, the reduction is lesser. The percentages of flow reduction between the Waller/Fort Bend County line and Richmond Gage are shown on **Table 3**.

TABLE 3: Flow Reduction Percentage from Waller/Fort Bend County Line to Richmond Gage

Location	Storm Event	Flows (cfs)	Peak Flow Reduction Percentage at US 90A
Waller/Fort Bend County	91	96,200	
Richmond Gage (US 90A)	91	94,000	2.34 %
Waller/Fort Bend County	1%	171,700	
Richmond Gage (US 90A)	1%	164,000	4.70 %

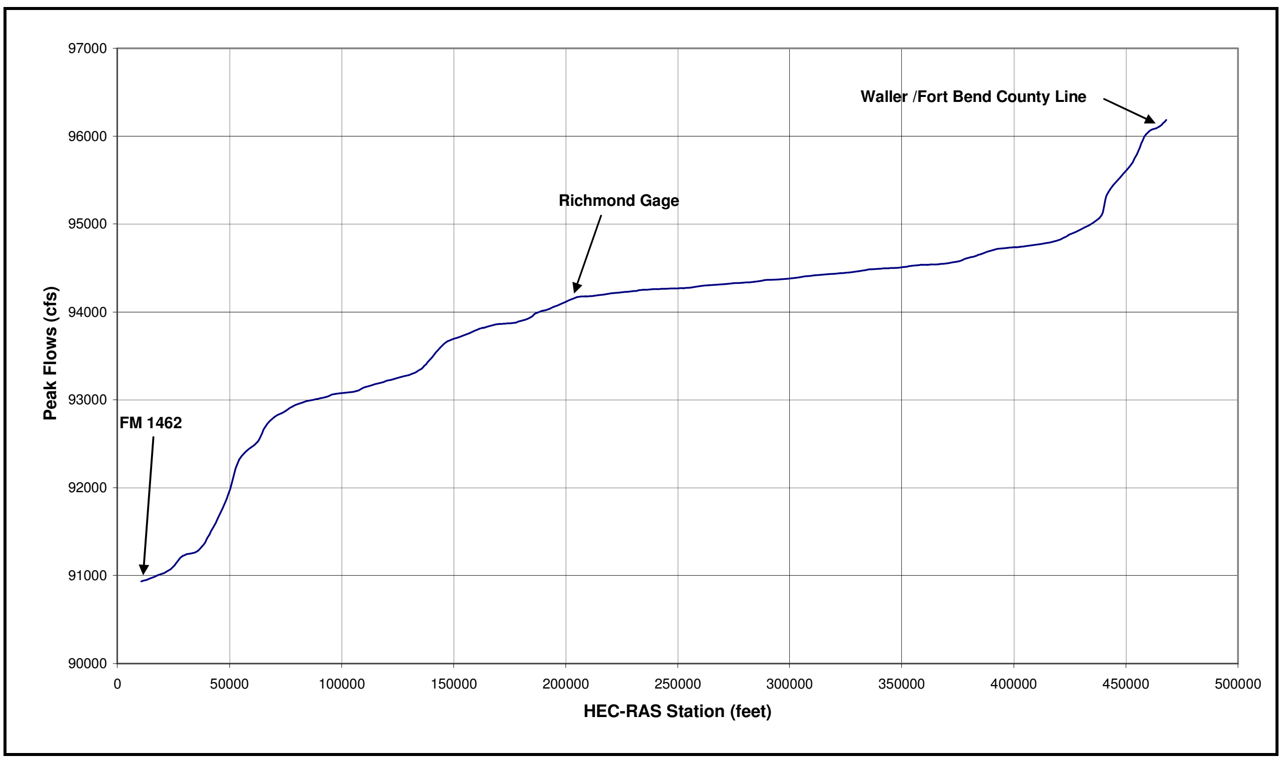

Figure 5: Calculated Flow Distribution for Brazos River in the 1991 Storm Event

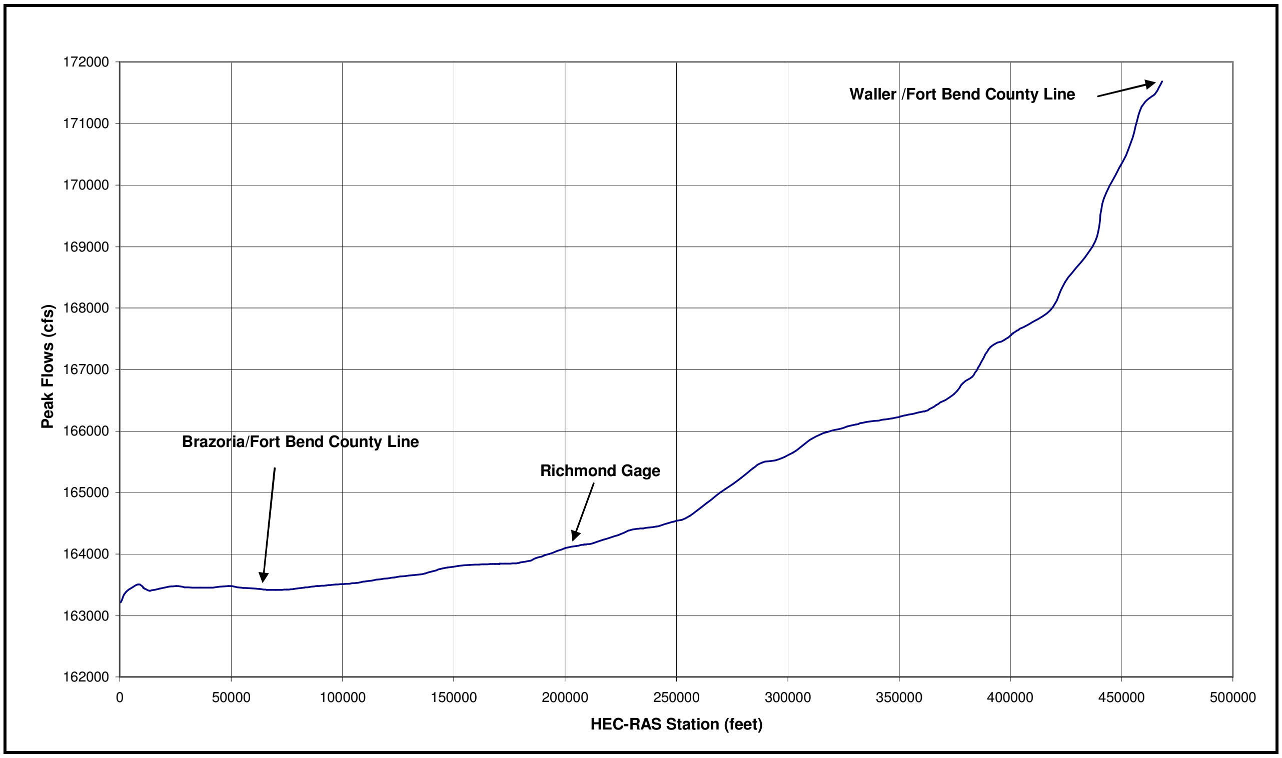

Figure 6: Calculated Flow Distribution for Brazos River in the 1% Storm Event

The flow reduction between Richmond and Rosharon is less probably due to the high stage used at the Rosharon gage. The flow situation at Rosharon is complex due to the overflow between the Brazos River and Oyster Creek in this area. Since HEC-RAS does not model a 2-dimensional flow condition, computation of the Rosharon flow is provided for illustration only. Since the flow reduction between Richmond and Rosharon is small, it is therefore assumed that there is no flow reduction between Richmond and the north side of the Brazoria county line. Along the Brazoria county line, the flow reduction (computed using a 2-dimensional analysis) used in the Brazoria FIS model is applied.

The unsteady HEC-RAS results showed that most of the attenuation from Hempstead Gage to Richmond Gage would occur in Waller County. The results were validated by the evaluation of the topography and the effective Brazos River floodplain in Waller County and Fort Bend County (see **Figure 7**). The proposed flow distribution of 1991 and 1% storm event from Waller/Fort Bend County Line to Richmond Gage (US 90A) are shown on **Table 4.**

Table 4: Proposed Flow Distribution in 1991 and 1% Storm Event

Location	HEC-RAS Station (ft)	Dec 1991 event	1% Flood Event
Waller/Fort Bend County	468115	96,200 cfs	171,700cfs
Upstream of FM 1093	417909	94,800 cfs	168,000 cfs
Upstream of FM 723	302479	94,400 cfs	165,700 cfs
Richmond USGS Gage	208514	94,000 cfs	164,000 cfs
Brazoria/Fort Bend County	62793	94,000 cfs	162,000 cfs

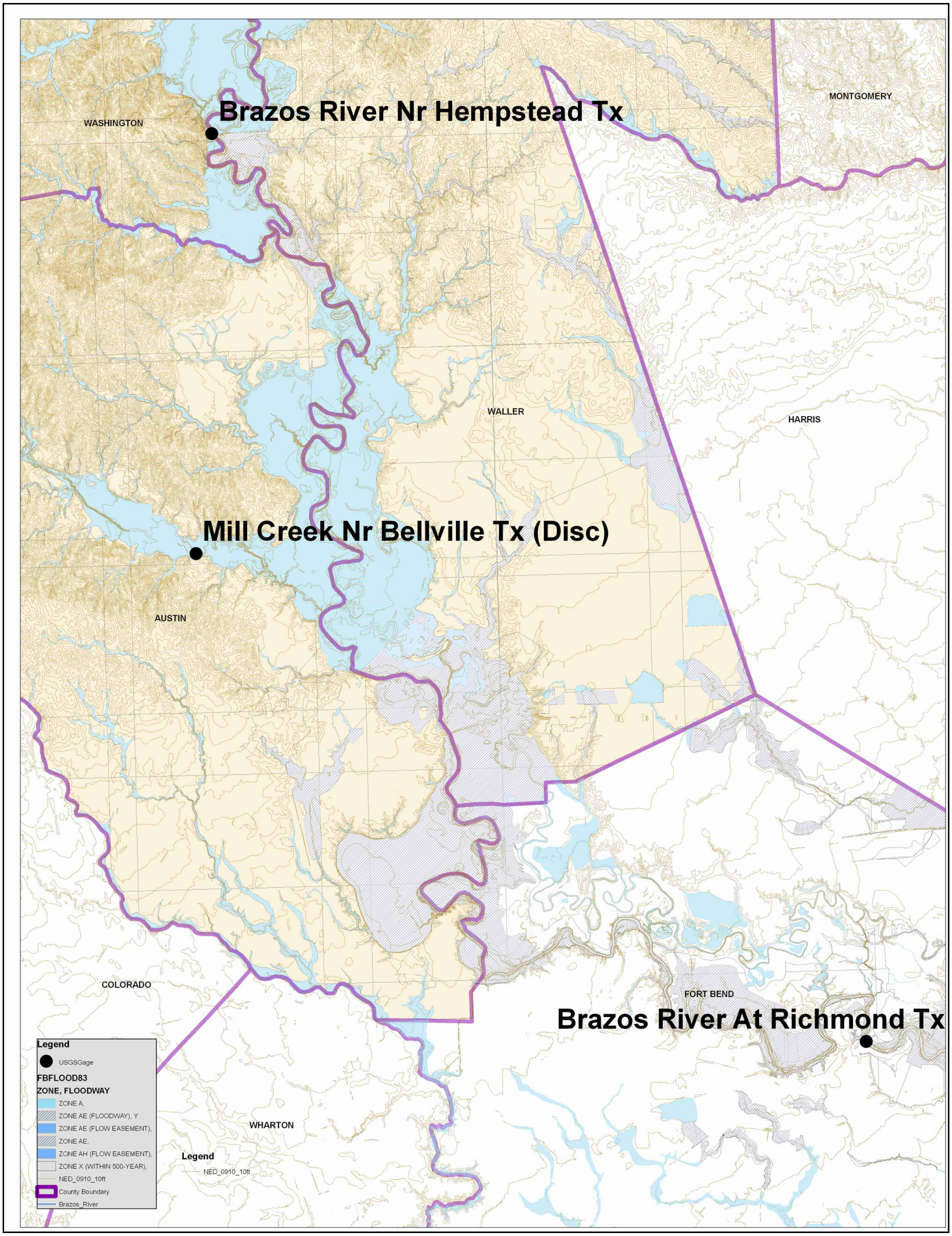

Figure 7: Effective Floodplain between Hempstead and Richmond USGS Gages

Tie-in Conditions at Brazoria and Waller Counties:

As shown on **Figure 1**, approximately 10 miles of the Brazos River from the confluence with Cow Creek to downstream of FM 1093 are parts of the county line between Fort Bend and Brazoria County. In 1986, the U.S. Army Corps of Engineers (USACE) study for the Brazoria County FIS determined that due to a lower topography to the east, high flows from the Brazos River along the Fort Bend / Brazoria County line overflowed in an easterly direction. Due to the overflow, the 1% flow of Brazos River (in the effective Brazoria FIS report) is reduced from 181,000 cfs at Brazoria/Fort Bend County line to 108,000 cfs at the confluence of Brazos River with Cow Creek. The Brazoria FIS report provided all relevant information regarding the USACE study and the determination of the overflow zone between the Brazos River and Oyster Creek. No other documentation could be found from the FEMA Library. Earlier discussion (2005) with the USACE Galveston District indicated that the District did not keep any documentation for this study.

With the availability of the 2006 Brazoria County LiDAR, the overflow zone was verified. **Figure 8** and **9** show the effective overflow zone of Brazos River overlaid on top of the Brazoria County LIDAR DEM and 2-foot contours.

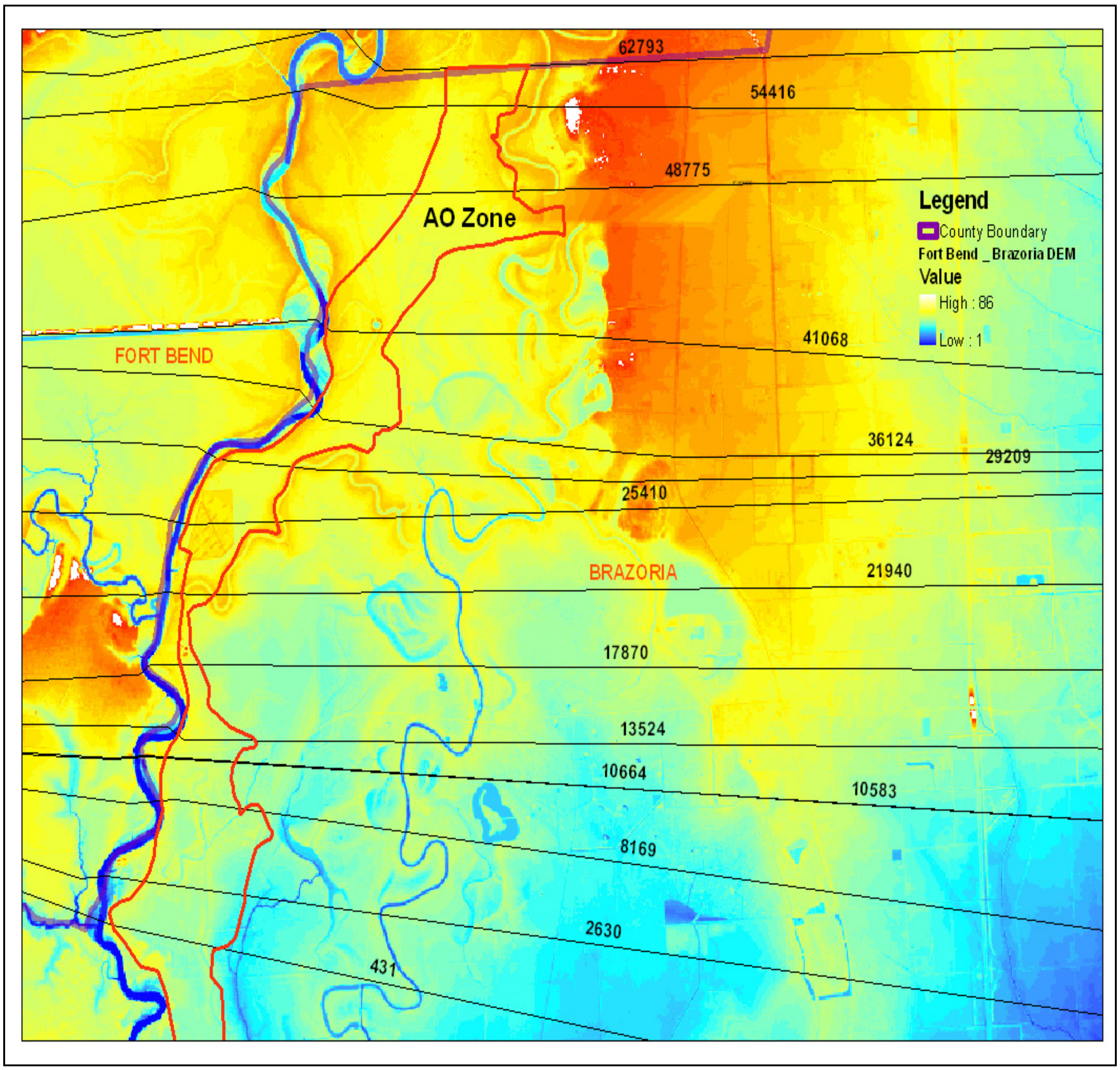

Figure 8: Effective Brazos River Overflow Zone with Brazoria County DEM

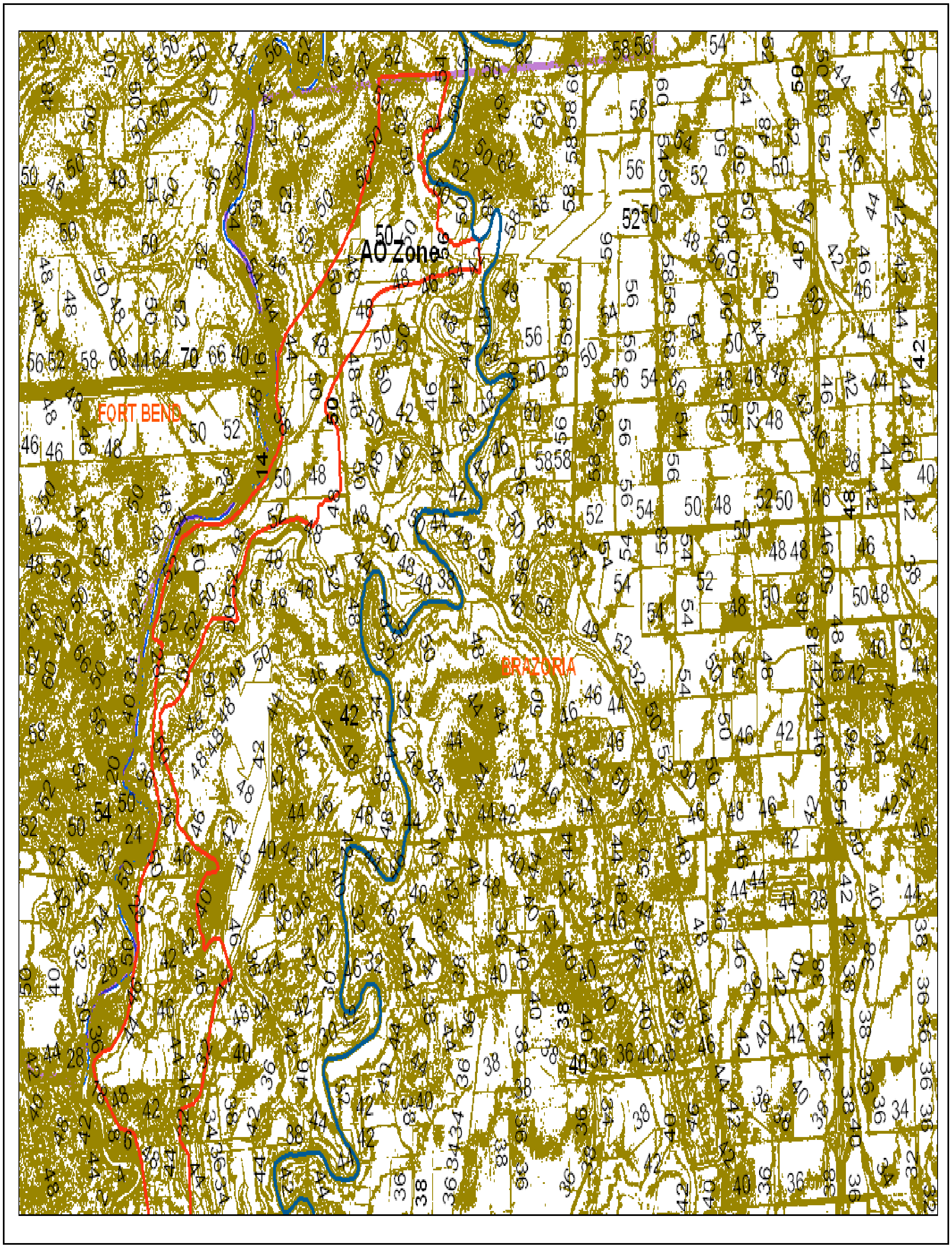

Figure 9: Effective Brazos River Overflow Zone with Brazoria County 2-foot Contours

Based on the flow distribution of the effective Brazos River HEC-2 model from the Brazoria County, the 1% flow distribution for the Brazos River HEC-RAS model was adjusted to reflect the gradual flow drop from 162,000 cfs at the Brazoria/Fort Bend County line (Station 62793) to 103,189 cfs at the confluence of Cow Creek and Brazos River (Station 431) (see **Table 5**).

Table 5 – 1% Flow Distribution for Brazos River Overflow Zone

Location	HEC-RAS Station	1% Flow (cfs)
Brazoria/Fort Bend County Line	62793	162,000
	54416	160,000
	48774	155,643
	41067	145,769
	36123	133,487
	29208	119,939
	25409	112,000
	21940	108,200
	17870	107,380
	13523	105,676
	10664	104,561
	8169	104,475
	2630	103,500
Cow Creek and Brazos River	431	103,189

Peak Flow Distribution

The peak flow distribution along the Brazos River was shown on **Table 6.**

Table 6: Flow Distribution for Brazos River					
Location	HEC-RAS Station (ft)	10% Flow	2% Flow	1% Flow	0.2% Flow
Waller/Fort Bend County	468115	105400	153900	171700	211500
Upstream of FM 1093	417909	103900	150600	168000	206900
Upstream of FM 723	302479	103400	148500	165700	204100
Richmond USGS Gage	208514	103000	147000	164000	202000
Brazoria/Fort Bend County Line	62793	103000	145000	162000	200000

	54416	103000	143000	160000	198000
	48774	103000	140844	155643	192430
	41067	103000	133570	145769	176356
	36123	103000	124521	133487	164898
	29208	103000	114541	119939	134357
	25409	103000	108000	112000	124000
	21940	103000	105100	108200	116000
	17870	103000	104524	107380	114464
	13523	103000	103328	105676	111275
	10664	96100	102545	104561	109187
	8169	96100	102487	104475	109031
	2630	96100	101722	103500	107200
Cow Creek and Brazos River	431	96100	101722	103189	106591