Interagency Flood Risk Management (InFRM)

Watershed Hydrology Assessment for the Trinity River Basin

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INTERAGENCY FLOOD RISK MANAGEMENT

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The InFRM Team

As flooding remains the leading cause of natural-disaster loss across the United States, the Interagency Flood Risk Management (InFRM) team brings together federal agencies with mission areas in water resources, hazard mitigation, and emergency management to leverage their unique skillsets, resources, and expertise to reduce long term flood risk throughout the region. The Federal Emergency Management Agency (FEMA) Region VI began sponsorship of the InFRM team in 2014 to better align Federal resources across the States of Texas, Oklahoma, New Mexico, Louisiana and Arkansas. The InFRM team is comprised of FEMA, the US Army Corps of Engineers (USACE), the US Geological Survey (USGS), and the National Weather Service (NWS), which serves under the National Oceanic and Atmospheric Administration (NOAA). One of the first initiatives undertaken by the InFRM team was performing Watershed Hydrology Assessments for large river basins in the region.

The Federal Emergency Management Agency (FEMA) funded the Watershed Hydrology Assessments to leverage the technical expertise, available data and scientific methodologies for hydrologic assessment through the InFRM team. This partnership allows FEMA to draw from the local knowledge, historic data and field staff of its partner agencies and develop forward leaning hydrologic assessments at a river basin level. These studies provide outcomes based on all available hydrologic approaches and provide suggestions for areas where the current flood hazard information may require update. FEMA will leverage these outcomes to assess the current flood hazard inventory, communicate areas of change with community technical and decision makers, and identify/prioritize future updates for Flood Insurance Rate Maps (FIRMs).

The US Army Corps of Engineers (USACE) has participated in the development of the Watershed Hydrology Assessments as a study manager and member of the InFRM team. USACE served in an advisory role in this study where USACE's expertise in the areas of hydraulics, hydrology, water management, and reservoir operations was required. USACE's primary scientific contributions to the study have been in its rainfall runoff watershed modeling and its reservoir analyses. The reservoir analyses in this study are based on USACE's first hand reservoir operations experience and the latest scientific techniques from USACE's Dam Safety program.

The U.S. Geological Survey (USGS) Oklahoma-Texas Water Science Center has participated in the development of this study as an adviser and member of the InFRM team. USGS served in an advisory role for this study where USGS' expertise in stream gaging, modeling, and statistics was requested. USGS's primary scientific contribution to the study has been statistical support for flood flow frequency analysis. This flood flow frequency analysis included USGS first hand stream gaging expertise as well as advanced statistical science.

NOAA National Weather Service (NWS) has participated in the development of this study as an adviser and member of the InFRM team. NOAA NWS served in an advisory role of this study where expertise in NOAA NWS' area of practice in water, weather and climate was requested. NOAA's primary scientific contribution to the study has been the NOAA Atlas 14 precipitation frequency estimates study for Texas. This precipitation-frequency atlas was jointly developed by participants from the InFRM team and published by NOAA. NOAA Atlas 14 is intended as the U.S. Government source of precipitation frequency estimates and associated information for the United States and U.S. affiliated territories.

More information on the InFRM team and its current initiatives can be found on the InFRM website at www.InFRM.us.

EXECUTIVE SUMMARY

The National Flood Insurance Program (NFIP) was created in 1968 to guide new development (and construction) away from flood hazard areas and to help transfer the costs of flood damages to the property owners through the payment of flood insurance premiums. The Federal Emergency Management Agency (FEMA) administers the NFIP. The standard that is generally used by FEMA in regulating development and in publishing flood insurance rate maps is the 1% annual chance (100-yr) flood. The 100-yr flood is defined as a flood which has a 1% chance of happening in any year. The factor that has the greatest influence on the depth and width of the 100-yr flood zone is the expected 1% annual chance (100-yr) flow value.

This report summarizes new analyses that were completed as part of a study to estimate the 1% annual chance (100-yr) flow, along with other frequency flows, for various stream reaches in the Trinity River Basin. This study was conducted for FEMA Region VI by an Interagency Flood Risk Management (InFRM) team. The InFRM team is a federal partnership and includes subject matter experts (SME) from FEMA, the U.S. Army Corps of Engineers (USACE), the U.S. Geological Survey (USGS), and the National Weather Service (NWS). In addition to the InFRM federal partnership, regional stakeholders such as the Tarrant Regional Water District (TRWD), the North Central Texas Council of Governments (NCTCOG), the Trinity River Authority (TRA), local communities , as well as local Architecture Engineering (AE) firms also participated in the update and review process for the study. This report is the product of a significant investment towards increasing resiliency against flood hazards given the extent: of existing information that was utilized, of updated and extensive analysis performed, and of interagency collaboration.

The InFRM team used several different methods, including statistical hydrology, rainfall-runoff modeling, and reservoir period-of-record simulations, to calculate the 1% annual chance (100-yr) flow and then compared those results to one another. The purpose of the study is to produce 100-yr flow values that are consistent and defendable across the basin.

The InFRM team used up-to-date statistical analysis along with state-of-the-art rainfall-runoff watershed modeling and reservoir modeling to estimate the 1% annual chance (100-yr) flow values throughout the Trinity River Basin. In the statistical analysis, the gage records were updated through the year 2016 or 2017 to include all recent major flood events. However, since statistical estimates inherently change with each additional year of data, their results were compared to the results of a detailed watershed model which is less likely to change over time. For example, the rainfall used in in the detailed watershed model came from the NOAA Atlas 14 precipitation atlas published in 2018 and changed less than 3% from the rainfall published in the NWS Technical Paper 40 (TP-40) in 1961, almost 60 years ago. This difference is from comparing the 1% annual chance 24-hour values from Dallas and Tarrant Counties. Rainfall values changed more significantly progressing Southeast through the basin, but the rainfall values upstream of the Dallas-Fort Worth metroplex have been much more stable over time than the statistical estimates of flood frequency, specifically for the 1% annual chance event.

Rainfall-runoff watershed modeling is used to simulate the physical processes that occur during storm events to simulate how water moves across the land surface and through the streams and rivers. A watershed model was built for the Trinity River Basin with input parameters that represented the physical characteristics of the watershed. After building the model, the InFRM team calibrated the model to verify that it was accurately simulating the response of the watershed to a range of observed flood events, including large events similar to a 1% annual chance (100-yr) flood. A total of seventeen recent storm events spanning 1991-2015 were used to fine tune the model. The watershed modeling developed represents a significant investment and is a tool available, at no charge, to communities and AE firms for the estimation of flood risk.

For the seventeen storm events used to fine tune the model, the availability of National Weather Service (NWS) hourly rainfall radar data allowed for more detailed fine tuning of the watershed model than would have been possible during earlier modeling efforts. The model calibration and verification process undertaken during this study substantially exceeds the standard of a typical FEMA floodplain study. The final model results accurately simulated the expected response of the watershed, as it reproduced the timing, shape, and magnitudes of the observed floods very well. Because these rainfall-runoff models have been calibrated to observed watershed responses to storm events, there is assurance that these models, when paired with best available precipitation frequency information, provide the best representation of flood risk and should be used in planning infrastructure and safely locating new neighborhoods and other development. An example plot of the modeled flow versus the recorded flow is shown on Figure ES.1, but many other similar figures are available in Appendix B – Rainfall Runoff Modeling in HEC-HMS.

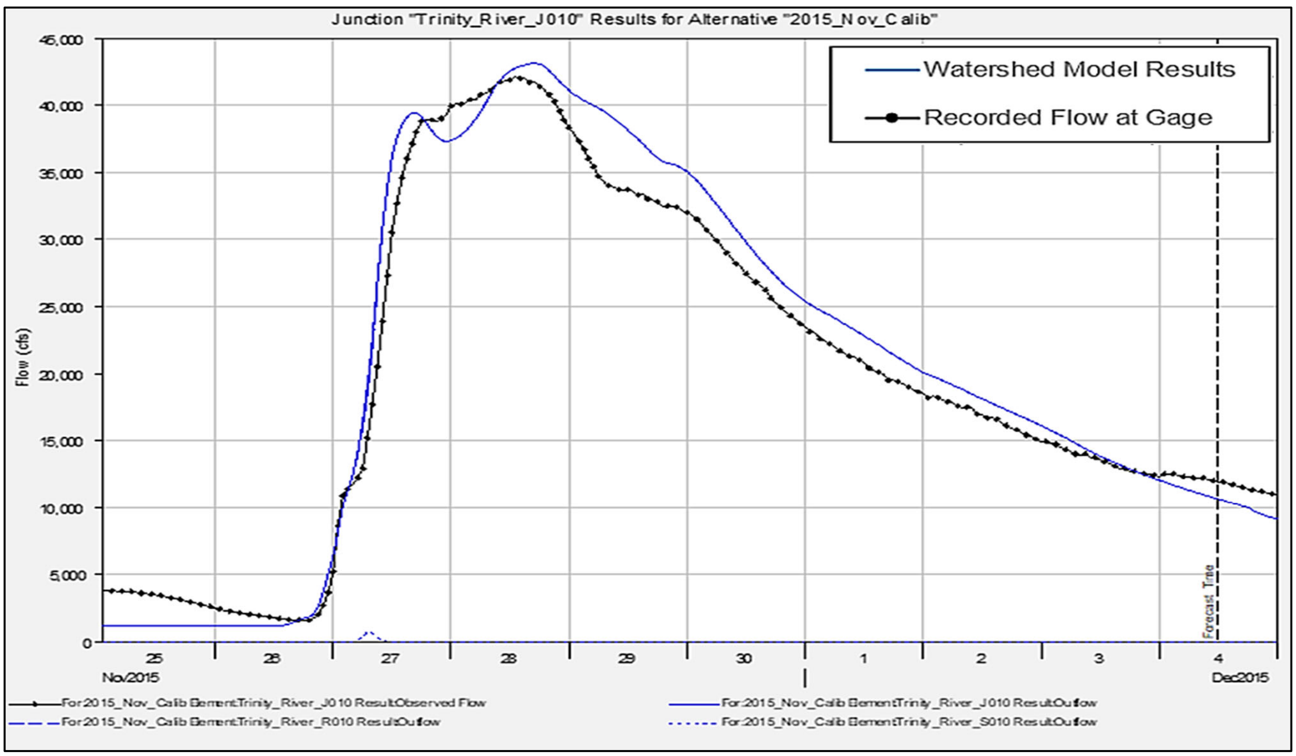


Figure ES.1: Example Watershed Model Results versus Recorded Flow

The 1% annual chance (100-yr) flow values were then calculated by applying the 100-yr storm to the watershed model. Rainfall estimates for the 100-yr storm are considered more reliable than statistical estimates for the 100-year flow due to the larger number of rainfall stations and the longer periods of time during which rainfall measurements have been made. The accuracy of those rainfall frequency estimates was further advanced by the release of NOAA Atlas 14 for Texas in 2018.

NOAA Atlas 14 is the U.S. Government source of precipitation frequency estimates and is the most accurate, up-to-date, and comprehensive study of rainfall depths in Texas. The regional approach used in NOAA Atlas 14 incorporated at least 1,000 cumulative years of daily data into each location's rainfall estimate, yielding better estimates of rare rainfall depths such as the 100-yr storm.

These new rainfall depths from NOAA Atlas 14 were applied to the calibrated watershed model for the Trinity River basin. After completing the model runs, the watershed model results were compared to all of the other results from the study. Comparison between watershed model results, statistical analyses, the flood of record, and the effective FEMA flows can be found in Chapter 10 (Comparison of Frequency Flow Estimates) of this report.

The final recommendations for the Trinity Watershed Hydrology Assessment were formulated through a rigorous process which required technical feedback and collaboration between all of the InFRM subject matter experts. This process included the following steps: (1) comparing the results of the various hydrologic methods to one another, (2) performing an investigation into the reasons for the differences in results at each location in the watershed, (3) selecting of the draft recommended methods, (4) performing interal and external technical reviews of the hydrologic analyses and the draft recommendations, and finally, (5) finalizing the study recommendations. After completing this process, the flows that were recommended for adoption by the InFRM team came from a combination of watershed model results using NOAA Atlas 14 uniform rain, elliptical storms, and reservoir studies.

Table ES.1 and Figures ES.2 and ES.3 compare the recommended flows from this study to previously published studies for a handful of locations in Dallas-Fort Worth. The comparisons include the existing conditions flows from currently effective FEMA Flood Insurance Studies (FIS) and the future 2055 flows from the Trinity River Corridor Development Certificate (CDC) program (NCTCOG, 2020). A complete list of the recommended flows and reservoir elevations from this study can be found in Chapter 11 of this report.

Table ES.1: Summary of 1% Annual Chance (100-yr) Flow Results (cfs) in Dallas-Fort Worth

Location	Currently Effective FEMA FIS Flow	CDC Future 2055 Flow	Recommended InFRM WHA Results
Mary's Creek at Benbrook, TX	43,400	-	63,100
Clear Fork Trinity River at Fort Worth, TX	29,800	50,100	72,100
West Fork Trinity River at Fort Worth, TX	47,000	69,400	75,200
West Fork Trinity River at Grand Prairie, TX	90,000	106,300	78,000
Elm Fork Trinity River near Carrollton, TX	43,500	48,200	37,200
Trinity River at Dallas, TX	115,800	128,600	113,100
Trinity River below Dallas, TX	119,300	130,200	116,700

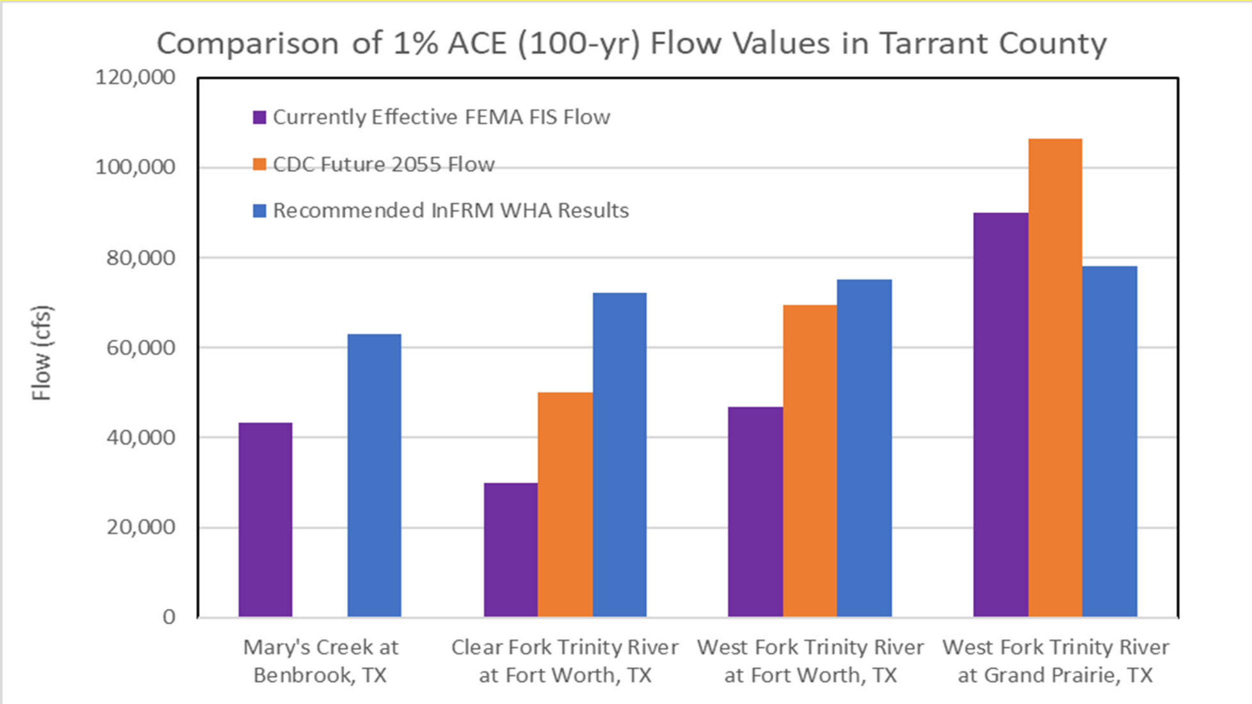


Figure ES.2: Comparison of 1% Annual Chance (100-yr) Flow Results (cfs) in Tarrant County

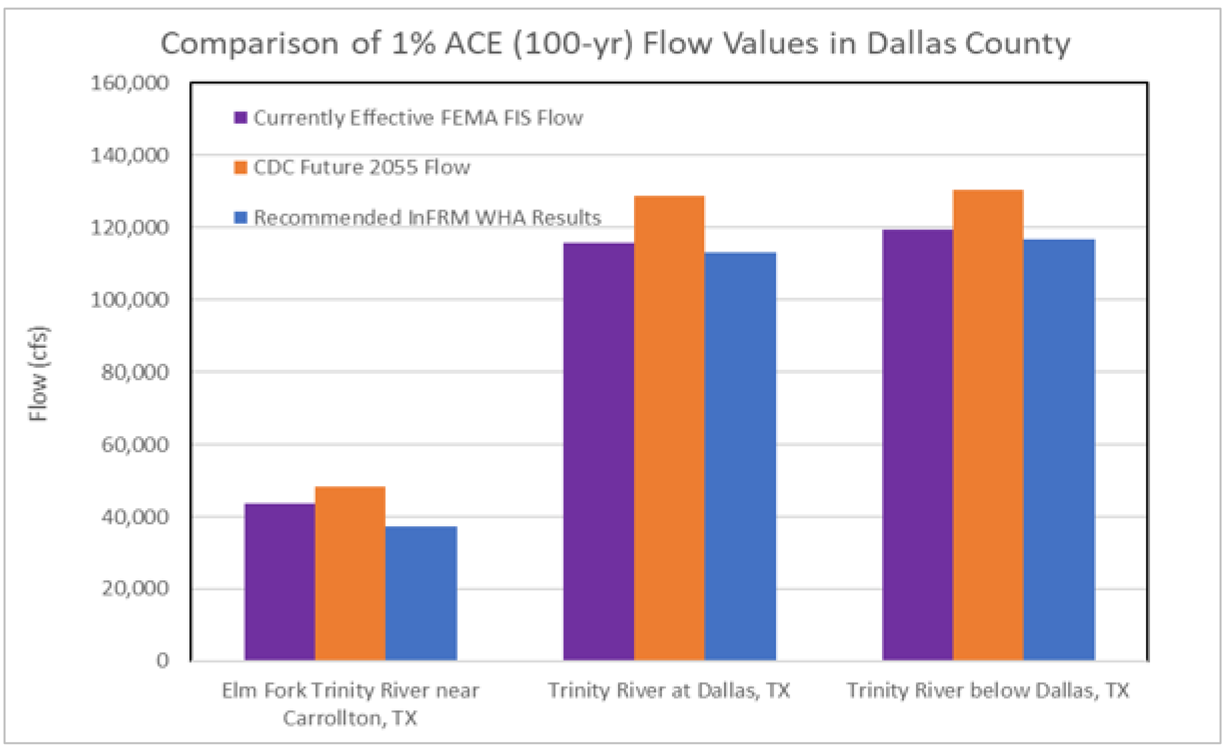


Figure ES.3: Comparison of 1% Annual Chance (100-yr) Flow Results (cfs) in Dallas County

The largest increases in the 1% annual chance (100-yr) flow estimates occurred in certain areas of Tarrant County, as shown in Figure ES.2. From this figure, one may observe that the recommended 1% flows from this study are significantly higher than both the effective FIS and the future CDC flows in Fort Worth, Texas. This increase in the 1% flow estimate in Fort Worth is due primarily to a better understanding of the response of the Mary's Creek watershed to large rainfall events.

The current study used a watershed model that was calibrated to match the timing, shape, and magnitude of the observed flows at the stream gage on Mary's Creek. This gage was not used to calibrate the models from any of the previous studies shown here. In fact, the gage was not even in existence at the time that the original FIS was published, Figure ES.4 illustrates the differences in the assumed response of the Mary's Creek watershed between the current study and the previous FIS. The new modeling results were calibrated to match the quicker and flashier runoff response that was recorded in the observed flows at the gage, whereas the model from the previous FIS study did not have a gage available for calibration and assumed a much slower watershed response for Mary's Creek. More information on Mary's Creek and the differences in results can be found in Chapter 10 of this report.

The increases in the peak flows from Mary's Creek drove the increases in flow on the Fort Worth reaches of the Clear Fork and the West Fork. By the time one reaches the West Fork Trinity River at Grand Prairie, the effect of Mary's Creek becomes negligible, and the recommended 1% flow estimate from this study is actually lower than the currently effective FIS flow. In Dallas County and in most other parts of the Trinity River watershed, there is a much smaller difference between the recommended flows from this study versus the effective FIS flows, as shown in Figure ES.3.

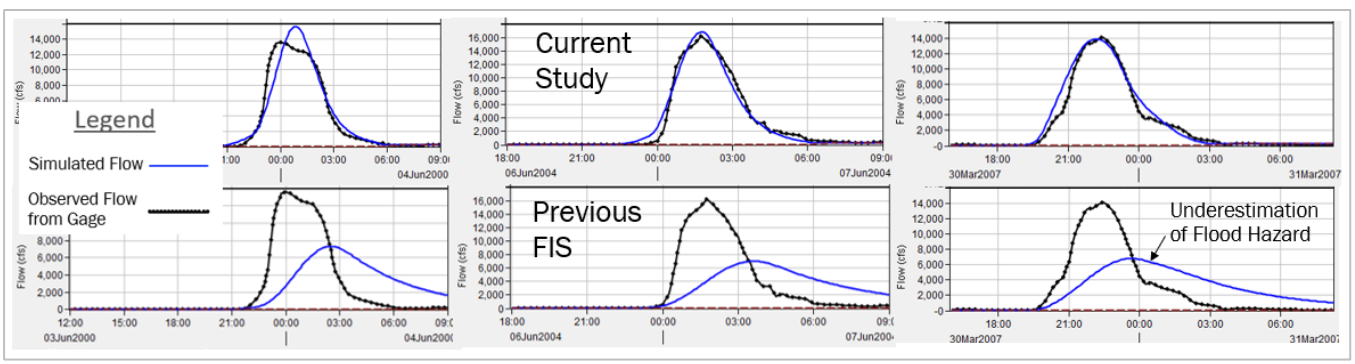


Figure ES.4: Model Results versus Recorded Flow at the Mary's Creek Gage

The recommended flows from this study represent the best available estimate of flood risk for the larger streams in the Trinity River basin based on multiple state-of-the-art hydrologic methods performed by an expert team of engineers and scientists from multiple federal agencies as well as the collaboration and oversight of regional stakeholders. For the smaller tributaries within the Trinity River basin, the new flows from the watershed model provide a good starting point which could be further refined by adding additional subbasins and using methodologies that are consistent with this study. The recommended flows presented in this report can be adopted by communities to revise their flood insurance rate maps, better manage development, and inform residents on their level of flood risk, resulting in more resilient communities where life and property is better protected against flood disasters.

As a result of the level of investment, analyses, and collaboration that went into this Trinity Watershed Hydrology Assessment, the flood risk estimates contained in this report are recommended as the basis for future NFIP studies or other federal flood risk studies. These federally developed modeling results form a consistent understanding of hydrology across the Trinity Watershed, a key requirement outlined in FEMA's General Hydrologic Considerations Guidance. The modeling used to produce these flood risk estimates is available, at no charge, to communities and AE firms.

1 Study Background and Purpose

In 1968, Congress passed the National Flood Insurance Act to correct some of the shortcomings of the traditional flood control and flood relief programs. The NFIP was created to:

- Transfer the costs of private property flood losses to the property owners through flood insurance premiums.
- Provide property owners with financial assistance after floods that do not warrant federal disaster aid.
- Guide development away from flood hazard areas.
- Require that new construction be built in ways that would minimize or prevent damage during a flood.

The NFIP program is administered by the FEMA within the Department of Homeland Security. The NFIP is charged with determination of the 1% annual chance flood risk and with mapping that flood risk on the Flood Insurance Rate Maps (FIRMs). FEMA Region VI has an inventory of hundreds of thousands of river miles that are in need of flood risk mapping updates or validation. FEMA has historically maintained the FIRMs at a community and county level, but recently shifted (2010) to analyzing flood analysis at a watershed level. This transition to watershed based analysis requires a broader flood risk assessment than has historically been undertaken. Early in 2015, the Water Resources Branch of the USACE Fort Worth District began talking with FEMA Region VI representatives on ways that USACE's new basin-wide models could be leveraged in FEMA's flood risk mapping program.

In 2013, USACE established a program, known as Corps Water Management System (CWMS), to develop a comprehensive suite of models for every basin across the United States which contains a USACE asset. This modeling represents in excess of a $125 million dollar investment and provides the tools necessary to perform flood risk assessments at a larger watershed scale. Representatives of FEMA Region VI attended the CWMS implementation handoff meetings for the Trinity River and other basins. Subsequent discussions resulted in an interagency partnership between FEMA Region VI and USACE to produce basin-wide hydrology from these models for FEMA flood risk mapping. Additionally, USACE, the NWS and the USGS have conducted numerous hydrologic studies across Region VI, at the watershed and local scales, which can be leveraged for watershed scale flood risk assessments.

The objective of this interagency flood risk program is to establish consistent flood risk hydrology estimates across large river basins. These watershed assessments will examine the hydrology across the entire basin, reviewing non-stationary influences such as regulation and land use changes, to ensure all variables affecting flood risk in the watersheds are considered. The studies' scope includes a multi-layered analysis with the purpose of producing flood frequency discharges that are consistent and defendable across a given basin. The multi-layered analysis employs a range of hydrologic methods (e.g. numerical modeling, statistical hydrology, etc.) to examine all available data affecting the hydrologic processes within the watersheds. The end product of these basin-wide hydrology studies is a hydrology report for use as a reference to evaluate against existing studies and also to support new local studies. These watershed hydrology assessments will also provide a tool set for use on local studies to provide the additional detail necessary to develop frequency flows at a smaller scale.

The basin-wide hydrology study for the Trinity River Basin is being conducted for FEMA Region VI by the InFRM team which includes representatives from USACE, USGS, and NWS. The scope of this basin-wide hydrology study includes a multi-layered analysis with the purpose of producing flood frequency estimates that are consistent and defendable across the basin.

This report summarizes the hydrologic analyses that were completed to estimate frequency peak stream flows for reaches throughout the Trinity River Basin. The results of all hydrologic analyses and the recommended frequency discharges are summarized herein.

1.1 STUDY TEAM MEMBERS

Table 1.1 lists the primary InFRM team members who participated in the development of the Trinity River Basin Watershed Hydrology Assessment. Landon Erickson, a Civil Engineer from USACE Fort Worth District, served as the team lead for this study. In addition to those listed, the InFRM team would also like to acknowledge the many others who served supervisory and support roles during this study.

Table 1.1: Study Team Members

	Name	Agency	Office
1	Dr. William Asquith	USGS	Lubbock
2	Allen Avance, P.E.	USACE	Fort Worth
3	Frank Bell, P.E.	NWS	WGRFC
4	Simeon Benson, P.E.	USACE	Fort Worth
5	Kristine Blickenstaff, P.E.	USGS	Fort Worth
6	Jerry Cotter, P.E.	USACE	Fort Worth
7	Waleska Echevarria-Doyle	USACE	ERDC
8	Landon Erickson, P.E.	USACE	Fort Worth
9	Heitem Ghanuni, P.E.	USACE	Fort Worth
10	Bret Higginbotham, P.E.	USACE	Fort Worth
11	Diane Howe	FEMA	Region 6
12	John Hunter, P.E.	USACE	Fort Worth
13	Alan Johnson	FEMA	Region 6
14	Kris Lander, P.E.	NWS	WGRFC
15	Craig Loftin, P.E.	USACE	Fort Worth
16	Paul McKee	NWS	WGRFC
17	Darla McVan	USACE	ERDC
18	James Moffitt	USACE	Fort Worth
19	Helena Mosser, P.E.	USACE	Fort Worth
20	Steve Pilney	USACE	Fort Worth
21	Marielys Ramos-Villanueva	USACE	ERDC
22	Sam Rendon	USGS	Fort Worth
23	Max Strickler, CFM	USACE	Fort Worth
24	Stephen Turnbull	USACE	ERDC
25	Sam Wallace	USGS	Fort Worth
26	Josh Willis	USACE	Fort Worth
27	Elizabeth Savage, P.E.	FEMA Support	Region 6

1.2 TECHNICAL REVIEW PROCESS

The InFRM Hydrology Assessments undergo a rigorous review process. Numerous peer reviews are performed by InFRM team members throughout the study. Each model, analysis, and technical product is peer reviewed as it is developed by an InFRM Subject Matter Expert (SME). Any technical issues that are discovered during the review process are thoroughly discussed and resolved, often with input from multiple team members. This same review process is also applied to the process of comparing and selecting final results. The draft results are shared with the rest of the InFRM team, and input is solicited from multiple subject matter experts. The draft study recommendations are then documented in the draft report.

The InFRM Academic Council also reviewed the methods and results of the InFRM Trinity Hydrology Assessment. The InFRM Academic Council is comprised of a select group of professors from local universities with unique skillsets, resources, and regional expertise in water resources and hydrology. Their involvement provides an independent and unbiased review of the InFRM team's methods and results. Collaboration with the InFRM Academic Council also helps the InFRM team to stay abreast with the latest advances in hydrologic science and technology. The primary InFRM Academic Council reviewers for the Trinity Hydrology Assessment were Dr. Nick Fang from the University of Texas at Arlington and Dr. Phil Bedient from Rice University. Comments from the InFRM Academic Council are included in Appendix G: Review Comments.

2 Trinity River Basin

2.1 WATERSHED AND RIVER SYSTEM DESCRIPTION

The Trinity River watershed is located in north central Texas within the Fort Worth District of the U.S Army Corps of Engineers and flows southeast to the Gulf of Mexico. The Trinity River watershed has a drainage area of 17,969 square miles. The Trinity River Basin drains all or part of 37 counties which includes the Dallas/Fort Worth Metropolitan area that is comprised of 7.5 million people. The West Fork Trinity River begins in Archer County and flow in a southeasterly direction for approximately 715 miles to empty into the Gulf of Mexico through the Trinity Bay and Galveston Bay. There are also approximately 2,000 miles of major tributaries that drain into the Trinity River.

The Trinity River has four upstream branches, the West Fork, the Clear Fork, the Elm Fork, and the East Fork Trinity River. The significant tributaries of the Trinity River, from upstream to downstream, include Mountain Creek, Denton Creek, Cedar Creek, Chambers Creek, and Richland Creek. The main stem of the Trinity River has an elevation of 400 feet at its confluence of West Fork and Elm Fork (Trinity River at Dallas) and slope of about 1.25 feet per mile in elevation between its source and its mouth.

The Trinity Basin is includes eight USACE reservoir projects of which six are located in or near the Dallas/Fort Worth metropolitan area. The reservoir projects are: Benbrook Lake (on Clear Fork Trinity River), Joe Pool Lake (on Mountain Creek), Grapevine Lake (on Denton Creek), Ray Roberts Lake (on Elm Fork Trinity River), Lewisville Lake (on Elm Fork Trinity River), and Lavon Lake (on East Fork Trinity River). The additional USACE reservoirs on the lower portion of the Trinity River watershed are Navarro Mills Lake (on Richland Creek) and Bardwell Lake (on Waxahachie Creek). Project purposes for each project includes: flood control, water supply, recreation, and fish and wildlife.

The Trinity River Watershed rises on the North Central Prairies and courses southwest to the Coastal Prairies and Marsh. The upper Trinity Basin has rolling topography and narrow stream channels. Soils in the region are deep to shallow clay, clay loam, and sandy loam that support elms, sycamores, willows, oaks, junipers, mesquites, and grasses. The middle and lower Trinity Basin is gently rolling to flat terrain with wide, shallow stream channels. Clay and sandy loams predominate and support water-tolerant hardwoods, conifers, and grasses.

The precipitation varies from northwest to southeast portion of the basin. The northern portion of the basin receives 35-40 inches of precipitation, on average, each year. As one travels southeast, the average annual precipitation exceeds 50 inches. The basin, particularly in the southeast, can experience extremely intense precipitation events capable of producing staggering rainfall totals. These systems range from intense thunderstorms to hurricanes.

The Trinity River main strem starts at the confluence of the Elm Fork and West Fork in Dallas Texas. Each USACE reservoir has a control or maximum allowable release as identified within the water control manual for that reservoir. The control limit at Dallas is 13,000 cfs for the combined releases of the five USACE reservoirs and water supply reservoirs upstream. The limit increases to 15,000 cfs at Rosser, TX below the East Fork confluence and again increases to 24,000 cfs at Oakwood, TX below the Richland Creek confluence.

The Clear Fork Trinity River, one of four forks that form the Trinity River, rises two miles south of Gibtown in extreme southeastern Jack County and flows east for five miles, then turns southeast and flows down a straight valley for 41 miles into Benbrook Lake which has a drainage area of 429 sq mi. The Clear Fork flows 14.5 miles to the confluence of the West Fork Trinity River through the Clear Fork Levee system in Fort Worth. Flows are controlled to 3,000 cfs along the reach From Benbrook Lake to the West Fork Trinity River confluence. The reach between the West and Clear Fork confluence and the West and Elm Fork confluence is controlled to 6,000 cfs. The majority of this 54 mile reach does not have levees, however does flow through urban terrain.

The West Fork Trinity River, one of four forks that form the Trinity River, forms in southern Archer County and flows southeast for approximately 145 miles to join with the Clear Fork in Fort Worth. Three water supply reservoirs-Lake Bridgeport, Eagle Mountain Lake, and Lake Worth, are located at various intervals along the West Fork. During flood events, their releases impact the ability for USACE reservoirs above the Trinity River at Dallas to make flood releases.

Mountain Creek, a tributary of the West Fork, forms in the northern part of Johnson County, and flows 37 miles to converge with the West Fork. Joe Pool Lake is located at river mile 11 and has a drainage area of 232 sq mi. The control limit below Joe Pool Lake along Mountain Creek to the West Fork is 4,000 cfs. Joe Pool Lake releases flow 7 miles downstream into Mountain Creek Reservoir. Mountain Creek Reservoir is a water supply lake, and affects Joe Pool Lake releases in flooding scenarios.

The Elm Fork Trinity River, one of four forks that form the Trinity River, forms in Montague County and flows approximately 85 miles southeast meeting the West Fork in Dallas Texas to create the main stream of the Trinity River. Releases from Ray Roberts will be made so that the releases from Lewisville will not exceed the control point flow at Carrollton of 7,000 cfs. Lewisville Lake is located at river mile 30 of the Elm Fork and has a drainage area of 1,660 sq mi (including Ray Roberts Lake's drainage area). Denton Creek converges with the Elm Fork 12 miles downstream of Lewisville Lake.

Denton Creek, a tributary of the Elm Fork Trinity River, rises midway between the towns of Bowie and Montague in Montague County, and flows southeast for approximately 50 miles into Grapevine Lake. Grapevine Lake has a drainage area of 695 sq mi. Denton Creek flows 6 miles to converge with the Elm Fork and has a control of 2,000cfs along this reach. Levees protect dense urban areas below Grapevine Lake along Denton Creek. The 18 mile reach from the confluence of Denton Creek and Elm Fork to the confluence of the Elm Fork and West Fork has a 7,000 cfs control flow limit.

The East Fork Trinity River, one of four forks that form the Trinity River, originates in the southern part of Grayson County, and flows south for approximately 110 miles to the confluence of the Trinity River. Lavon Lake is located at river mile 56 and has a drainage area of 770 sq mi. Lavon Lake releases feed directly into Ray Hubbard Lake which is a water supply lake. The control limit below Lavon and Ray Hubbard Lakes along the East Fork to the Trinity River is 8,000 cfs.

Richland Creek, a tributary of the Trinity River, rises in eastern Hill County about 4 miles west of Itasca, TX, and flows east for approximately 97 miles to the Trinity River. Navarro Mills Lake is located on river mile 64 and has a drainage area of 320 sq mi. The control limit below Navarro Mills Lake along Richland Creek is 2,000cfs. Releases from Navarro Mills Lake flow into Richland-Chambers Reservoir which is a water supply lake. Releases from Richland-Chambers are affected by Navarro Mills Lake flood releases.

Waxahachie Creek, a tributary of Chambers Creek, originates in Ellis County near Midlothian, TX, and flows southeast for approximately 31 miles converging at Chambers Creek river mile 41.5. Bardwell Lake is located at river mile 5 on Waxahachie Creek and has a drainage area of 178 sq mi. Chambers Creek, a tributary of Richland Creek, flows east into Richland-Chambers Reservoir. The control below Bardwell Lake along Waxahachie Creek is 2,000cfs and along Chambers Creek is 4,000 cfs.

The primary purpose of the USACE projects is to prevent flood damages to the Dallas/Fort Worth metropolitan area but other purposes include hydropower generation, fish and wildlife, water quality, recreational use and water supply. The regulation of flood and conservation storage in each reservoir is balanced with the regulation of storage in all of the other reservoirs in the basin.

Figure 2.1 displays the Trinity River watershed's location. Figure 2.2 displays the Trinity River Watershed's Major Tributaries and Water Management Projects. Figure 2.3 focuses on the Dallas/Fort Worth metropolitan area and shows the location of the six USACE reservoir projects – Benbrook, Joe Pool, Grapevine, Ray Roberts, Lewisville, and Lavon Lakes.

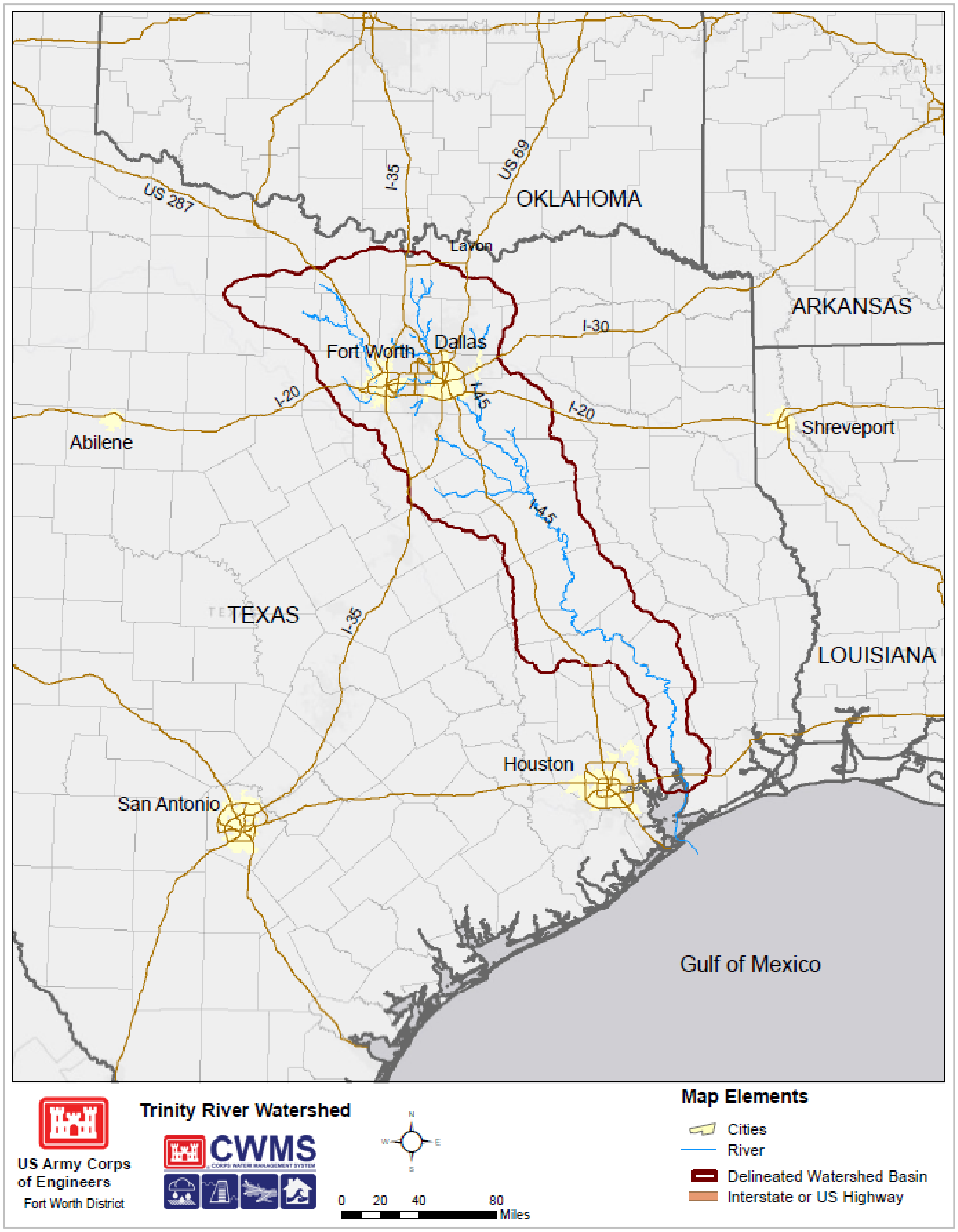


Figure 2.1: Trinity River Watershed Location

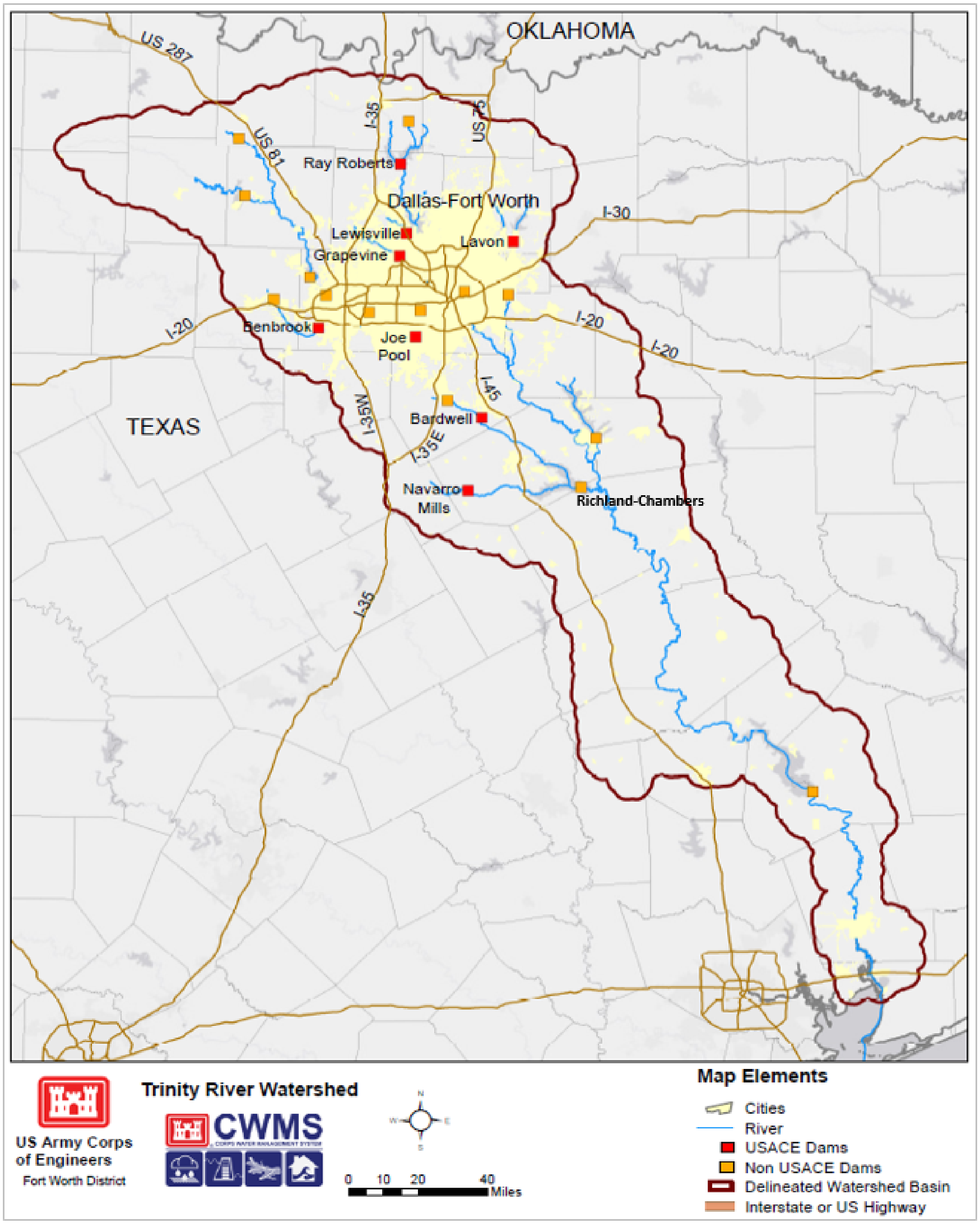


Figure 2.2: Trinity River Watershed Major Tributaries and Water Management Projects

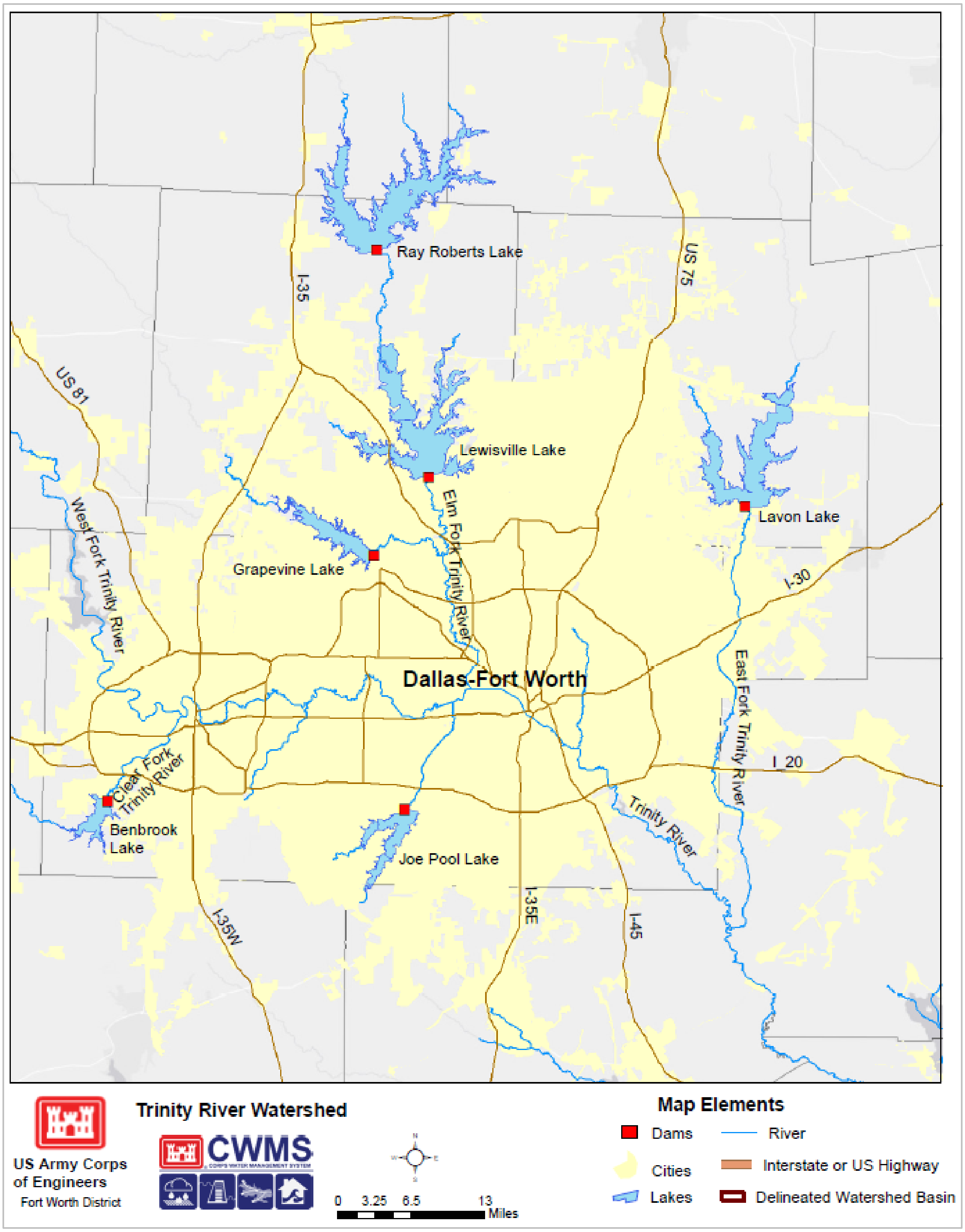


Figure 2.3: Dallas-Fort Worth Major Tributaries and Water Managemet Projects

2.2 MAJOR FLOODS IN THE BASIN

The Trinity River basin has a history of flooding that spans back to 1908 and 1922, when major flood stages were recorded at Dallas and Fort Worth Texas. Available streamflow records show that major floods have been experienced over nearly all areas of the Trinity River Basin. The following sections summarize information on some of the major floods in the Trinity basin of the last 30 years, including the April-May 1990, December 1991, May 2015, and October 2015 floods on the Trinity River. Major floods at stream gages in the Trinity River basin are listed in Table 2.1.

Table 2.1: Major Floods in the Trinity River Basin

Date of Flood	Event used for Model Calibration	Observed Peak Flow (cfs)			
		West Fork at Fort Worth (USGS 08048000)*	Trinity River at Dallas (USGS 08057000) **	Trinity River near Rosser(USGS 08062500) ***	Trinity River near Oakwood (USGS 08065000)****
May-1890					180,000
May-1908			184,000	133,000	164,000
Dec-1913			44,500		
Apr-1916			54,700		
Nov-1918			50,300		
May-1920			54,000		
Apr-1922		85,000	75,100		
Dec-1923		-	43,100		
May-1930					84,400
Jan-1932			44,000		-
May-1935			76,700		
Feb-1938			67,500		
Jun-1941			77,000	55,300	-
Apr-1942			111,000	150,000	153,000
May-1944					111,000
Mar-1945			52,900	66,600	140,000
Jun-1946				54,800	
Feb-1948			46,300		
May-1949		64,300	82,500	51,900	
Apr-1957		-	-	-	91,800
May-1957			75,300	56,000	-
May-1966				63,400	
May-1969			67,000	56,200	83,700
Dec-1971				53,400	
Mar-1977					
Oct-1981				-	
May-1989			58,700	66,900	
May-1990		36,200	82,300	122,000	107,000
Dec-1991	Yes		62,200	92,900	106,000
May-1995				56,800	77,300
Jan-1998			-	-	76,700
Mar-2006			43,800		
Jun-2007	Yes				71,600

Date of Flood	Event used for Model Calibration	Observed Peak Flow (cfs)			
		West Fork at Fort Worth (USGS 08048000)*	Trinity River at Dallas (USGS 08057000) **	Trinity River near Rosser(USGS 08062500) ***	Trinity River near Oakwood (USGS 08065000)****
Sep-2010	Yes		44,200		-
May-2015	Yes		47,300	69,000	79,400
Oct-2015			-		103,000
Nov-2015	Yes		42,100	61,300	
Sep-2018		-	41,100	-	-

Notes:

1. Data retrieved from USGS Peak Streamflow for Texas database and only includes values near or above the current 10% annual chance value.

2. * Peak flood flows were affected at this gage by regulation since 1914. ** Peak flood flows were affected at this gage by regulation since 1913. *** Peak flood flows were affected at this gage by regulation since 1924. **** Peak flood flows were affected at this gage by regulation since 1923.

2.2.1 Upper Trinity Basin – April-May 1990 Storm

A large portion of State of Texas experienced above normal rainfall January through April and into May of 1990. The major storm systems in the latter part of April were the result of a cold front mixed with an upper level low and produced two frontal type storms which formed over north and west Texas from 17-20 April and 24-27 April 1990. The storm which occurred on 1-4 May 1990 was the result of cool surface air mixing with warm rising air from the south-southwest. The upper Trinity River Basin received 2 to 3 inches of rain from the April 17-20 storm. The April 24-27 storm was such that much of the upper basin received 6 to 8 inches. Precipitation at the Dallas/Fort Worth Airport (DFW) for the first four months of 1990 was 22.05 inches (12.42 inches above normal). The April precipitation at DFW was 6.90 inches (3.27 inches above normal). The May 1-4 storm resulted in most of the upper Trinity Basin receiving 4 to 6 inches of rain. Some rainfall extremes for May were; Aledo 7.76 inches, Anna 9.21 inches, Benbrook Dam 5.71 inches, Carrollton 6.55 inches, Farmersville 6.61 inches, Frisco 7.04 inches, Gordonville 6.91 inches, Gunter 7.22 inches, McKinney 3S 6.29 inches, and Pilot Point 6.1 inches.

The rains on May 1-4 resulted in a peak inflow of about 58,300 cfs into Benbrook Lake and caused the lake to rise to elevation 717.54 feet on May 3, setting a new record elevation. This was the third time that the project had spilled. The peak flow through the spillway notch was 6,650 cfs. The peak flow at the Clear Fork at Fort Worth gage was 20,900 cfs estimated from a peak stage of 16.80 feet on May 2. The peak flow at the West Fork at Fort Worth gage was 36,200 cfs with a peak stage of 9.91 feet on May 3.

Ray Roberts Lake peaked at elevation 644.44 feet or 157 percent of flood control storage on 03 May 1990, setting a new record elevation. This elevation is 3.94 feet above the top of the flood control pool and is only 1.06 feet below the spillway crest. The peak inflow into the lake was approximately 115,000 cfs. Lewisville Lake peaked at elevation 536.73 feet or 158 percent of flood control storage on May 4, 1990, setting a new record elevation. This elevation is 4.73 feet above the service spillway and produced an uncontrolled flow of 19,300 cfs as compared to peak inflow of approximately 235,000 cfs. Of the eight flood control lakes in the Trinity Basin, six attained new record peak elevations and four exceeded the top of their flood control pool.

On May 3, the daily inflow volume into Lake Lavon was 61,900 dsf with an estimated peak inflow of approximately 95,000 cfs. That evening, Lavon Lake set a record maximum elevation of 504.59 feet, while at the same time making surcharge releases. This lake elevation is 1.09 feet above the top of the flood control pool with the lake holding approximately 334,500 acre-feet of floodwater. This was the fifth time surcharge releases have been made from Lavon Dam and at the highest discharge rate ever, 54,000 cfs. The total inflow into Lavon Lake in the 2 months of April and May was almost half a million acre-feet. Lavon Lake experienced the highest annual inflow volume since impoundment, nearly 900,000 acre-feet.

The flooding resulted in the closing of many roads and bridges. Numerous levee systems along the Trinity River between Dallas County and Liberty County were overtopped and scoured. About 200 homes and businesses were flooded in the Rochester Park area of South Dallas. An estimated $30 million in damages was caused by the flooding in Dallas County. The Clear Creek gage near Sanger crested at 31 feet, which corresponded to a flow of approximately 15,000 cfs. The water level at this stage height was 6 feet above the top of bank. The Carrollton gage on the Elm Fork crested at 13.48 feet with a corresponding flow of 27,600 cfs. The Trinity River at Dallas gage peaked at 47 feet with an observed flow of 81,000 cfs. Releases from Lake Livingston reached a maximum of 100,800 cfs. This release surpassed the previous high release of 75,000 cfs in the 1973 flood. These releases produced a flow of 106,000 cfs with a record crest elevation of 30.07 feet at Liberty in southeast Texas.

2.2.2 Upper Trinity Basin – December 1991 Storm

On 18 December, a cold surface ridge had settled over Texas. At the same time, an upper level low over Arizona forced the jet streams through Mexico and into Texas drawing moisture out of the Pacific. The moist air in the middle and upper layers of the system was the catalyst for the rains that occurred over the next several days. This resulted in some 100,000 square miles in the eastern-half of Texas receiving in excess of 4 inches of rainfall. The heaviest rainfall fell along the Edwards Plateau where 12 to 16 inch rainfall totals were common. The month of December was one of the wettest in northern Texas since records began in 1898. December also saw one of its largest floods in Texas when measured in terms of water volume.

Most of the Trinity River Basin received rainfall amounts totaling between 4 and 6 inches during the 6-day period of December 18-23. In the Clear Fork watershed the recorded rainfall amounts were higher and are as follows: Aledo, 7.39 inches; Benbrook Dam, 7.11 inches; Cresson, 7.97 inches; and Weatherford, 8.52 inches. These weather stations recorded totals of nine and one-half to eleven inches during the month of December. The most intense rainfall occurred in the late morning hours of 20 December when nearly 3 inches fell throughout the Clear Fork watershed. The intense rain on the already saturated soil produced high runoff. The peak inflow into Benbrook Lake was about 48,500 cfs that afternoon. The lake continued to rise for several days, as gated releases were not made due to flooding downstream. On Christmas Day the lake peaked at elevation 712.30 feet, 2.30 feet above the spillway notch. This was the fourth time that the spillway was overtopped. The Clear Fork at Fort Worth peaked at a stage of 16.05 feet with an estimated flow of 18,000 cfs. The West Fork at Fort Worth peaked at a stage of 8.60 feet with an estimated flow of 28,200 cfs.

Some of the recorded rainfall amounts in the Elm Fork watershed were as follows: Denton 2SE 4.27 inches, Forestburg 5.60 inches, Frisco 6.11 inches, Gunter 6.41 inches, Lewisville Dam 6.61 inches, Muenster 4.58 inches, Pilot Point 5.80 inches, Slidell 6.09 inches, and Valley View 6.11 inches. This rainfall produced about 250,000 acre-feet of runoff, which raised Lewisville Lake from elevation 523 feet to 530 feet. The peak inflow into the lake was approximately 82,000 cfs. The Carrollton Gage on the Elm Fork crested at 10.32 feet with a flow of 11,500 cfs. The Trinity River at Dallas gage peaked at 44.44 feet with an observed flow of 62,200 cfs.

Substantial flooding occurred along the Trinity River from Grand Prairie through Dallas. In Grand Prairie, 11 homes, a concrete manufacturing plant and over 100 rental cars at a parking lot were flooded by high water up to 5 inches in depth. In Dallas, approximately 180 homes and 15 businesses received up to $4.5 million in damages from flooding. Around 100 homes were flooded up to several feet in depth at Rochester Park while 3 homes were flooded in the Cadillac Heights area south of Dallas.

2.2.3 Upper Trinity Basin – May 2015 Storm

During the spring of 2015, El Niño produced an active weather pattern across the Western United States. A persistent upper-level low in the northern polar jet stream dropped storm after storm down the Pacific coastline. These storms tracked into the central Plains. One cold front after another moved across Texas, and these fronts, led to flash flooding. Texas remained in an upper air flow pattern in May, which generated heavy rains. Many locations in north central Texas received 10 to 20 inch rainfall. Rainfall totals exceed 20 inches for the month in the DFW Metroplex and north towards the Red River. The statewide average monthly rainfall was a record 8.81 inches, and multiple local rainfall records were also set during the month.

The highest measured rainfall total in May was observed at 5ENE of Gainesville, TX, where 28.90 inches was recorded. DFW airport received 16.96 inches in May, where normal is 4.74 inches. Stations in the Clear Fork Trinity River Basin received 6-17 inches in a 3-week period, with a center at Burleson, which received 17.19 inches. Rainfall amounts in the Elm Fork Trinity River Basin received 9-28 inches in a 3-week period. Stations in the Denton Creek Basin received 12-22 inches in a 3-week period, with a center at Bowie, which received 21.65 inches. Rainfall amounts recorded in the Lavon Lake watershed during the last three weeks of the month were: Anna 18.7 inches, Lavon Dam 8.9 inches, and McKinney 3S 19.9 inches. Not only was this the wettest May of record, but May 2015 ranked the third highest monthly maximum precipitation since September 1898, according to historical records. These rains eliminated the multi-year drought for the entire state of Texas.

River flooding was state wide and lasted for weeks. The Trinity River flowed over its banks in various places from the head waters to the Gulf of Mexico. Most rivers and streams had multiple peak flows during these events with USGS gages rising 4 to 6 above flood stage. The Carrollton Gage on the Elm Fork crested at 13.12 feet with a flow of 26,700 cfs. The Trinity River at Dallas gage peaked at 41.98 feet with an observed flow of 47,300 cfs. Lewisville Lake elevation peaked at a new record of 537.01 feet, 5.01 feet above the spillway.

Lavon Lake had been 23 feet below its conservation pool elevation of 492 feet, at the beginning of the year. Due to the spring rains, the lake began to rise to the top of its conservation pool in late April. With continuing rains in May, the lake experienced high inflows and continued to rise an additional 12 feet, into the surcharge pool with a peak elevation of 504.12 feet. The total volume of inflow for the last three weeks in May was approximately 420,000 acre-feet. Tainter gate releases reached a rate of 24,800 cfs. This was the sixth time in the 61 year history, in which Lavon Lake had risen into the surcharge pool. At the beginning of the year, Lavon Lake was at its third lowest pool elevation since the conservation pool was raised in 1975, and by the end of May, the lake reached the second highest pool elevation. The May 2015 event resulted in the surcharge of all 8 USACE reservoirs.

2.2.4 Middle Trinity Basin – October 2015 Storm

The storms of October to November of 2015 produced record amounts of precipitation across the state, which exceeded the precipitation from the record storms earlier in the year in some regions. Record-setting precipitation across the state caused flooding in areas still recovering from the floods of May and June. These floods killed at least six people, damaged hundreds of homes, and closed roads throughout the state. Moisture and energy from the remnants of Hurricane Patricia contributed to significant rainfall and subsequent flooding across the state in late October. A wave of record breaking storms near Halloween followed by multiple rounds of intense storms throughout November overwhelmed the capacity of river systems multiple times in various locations throughout the state. Flooding was perhaps most severe in Navarro County where intense flooding made road closures and water rescues a relatively common occurrence throughout October and November. Over 100 roads sustained damage or were washed out in Navarro County. Portions of Interstate 45 were closed on the night of the 23rd and again on the 24th.

The heaviest rains fell between 23 and 31 October, with 15.78 inches at Athens, 14.41 inches at Bardwell Dam, 24.37 inches at Corsicana, 13.13 inches at Hillsboro, 14.16 inches at Maypearl, 23.26 inches at Navarro Mills Dam and 11.29 inches at Rosser. The heaviest rain fell on October 23rd with 16.70 inches at Navarro Mills Dam, and 15.20 inches at Corsicana.

The floods in October and November reached a stage of 31.31 feet on Ash Creek at Malone, 27.04 feet on Richland Creek at Mertens, 23.74 feet on Richland Creek at Dawson, and 44.86 feet on White Rock Creek at Irene. The resulting peak discharges during this time were 6,050 cfs at Malone, 1,480 cfs at Mertens, 5,520 cfs at Dawson, and 14,300 cfs at Irene. The Chambers Creek near Rice gage peaked at 31.83 feet with an observed flow of 36,400 cfs. Both Navarro Mills Lake and Richland-Chambers Lake reached record lake elevations during this time. Richland-Chambers Lake reached an elevation of 317.68 feet on October 24 and Navarro Mills Lake reached a peak elevation of 443.19 feet on October 31. These storms caused the Navarro Mills lake elevation to rise about 11 feet on October 24 and 20 feet between October 22 and October 31. The Navarro Mills lake inflow volume was approximately 86,150 acre-feet on October 24, and 173,560 acre-feet between October 22 and October 31.

The Trinity River near Rosser gage peaked at 32.08 feet feet with an observed flow of 32,300 cfs on October 26. The Trinity River near Oakwood gage peaked at 48.97 feet with an observed flow of 103,000 cfs on October 27.

Other major floods that have occurred in the Trinity River basin, along with their peak flow estimates, were listed in Table 2.1. Several of these floods were used as calibration events for this study's rainfall-runoff model, as denoted in the table. The dam and lake projects and major flood control channel projects of the Trinity River basin are listed in Table 2.2.

Table 2.2: Major Trinity River Basin Flood Control Projects

Project	Stream	Year of Completion
Anahuac Channel	Trinity River	1913
Lake Worth Dam	West Fork of the Trinity River	1914
Dallas Floodway	Trinity River	1930/(SPF Protection in 1950s)
Bridgeport Dam, TRWD Project	West Fork of the Trinity River	1932
Eagle Mountain Dam, TRWD Project	West Fork of the Trinity River	1934
Benbrook Dam	Clear Fork of the Trinity River	1952
Grapevine Dam	Denton Creek	1952
Lavon Dam	East Fork of the Trinity River	1953
Lewisville Dam	Elm Fork of the Trinity River	1955
Navarro Mills Dam	Richland Creek	1963
Bardwell Dam	Waxahachie Creek	1965
Joe B. Hogsett Dam, TRWD Project	Cedar Creek	1965
Big Fossil Creek Floodway	Big Fossil Creek	1968
Lake Livingston Dam, TRA Project	Trinity River	1969
Rockwall-Forney Dam	East Fork of the Trinity River	1968
Fort Worth Floodway	West and Clear Forks of the Trinity River	1970
Joe Pool Dam	Mountain Creek	1986
Ray Roberts Dam	Elm Fork of the Trinity River	1987
Richland Chambers Dam, TRWD Project	Richland Creek	1987
Wallisville Saltwater Barrier	Trinity River	1998
Duck Creek Channel Improvement	Duck Creek	1998

2.3 PREVIOUS HYDROLOGY STUDIES

The hydrology of the Trinity River and its tributaries has been analyzed many times over the years. Data and models from several existing hydrologic and hydraulic studies were available at the time of this study. Table 2.3 below summarizes some of the notable existing studies, models, and hydrologic information that were previously performed in the Trinity River basin.

Table 2.3: Previous Hydrologic Studies in the Trinity River Basin

Study Name	**River Extents**	**Frequency Flows**	**Hydrologic Methods**	**Description**
USACE CWMS Trinity River Basin Forexast Model, 2015	Trinity River Basin	No	Rainfall-runoff modeling	Forecast model developed for entire Trinity River Basin.
TRWD Forecast Model, 2013	West Fork upstream of Lake Worth Dam	No	Rainfall-runoff modeling	Model utilized regional Ct value to compute lag times.
USACE Upper Trinity Feasiblity Study, 1995	Clear Fork upstream of Benbrook Dam	Yes	Rainfall-runoff modeling	HEC-1 modeling developed with USACE Fort Worth District Urban Curve Equations.
USACE CDC HMS Model with 2005 Land Use, 2013	Area between Lake Worth Dam, Benbrook Dam, and Lewisville Dam downstream to Trinity at Five Mile Creek	Yes	Rainfall-runoff modeling	CDC HEC-HMS model with land use changed from 2055 to 2005 conditions. USACE Fort Worth District Urban Curve Equations used to recomputed model parameters.
USACE Dam Safety Modification Study for Lewisville Lake, 2010	Elm Fork Trinity upstream of Lewisville Dam	Yes	Rainfall-runoff modeling	Model utilized USACE Fort Worth District Urban Curve equations.
USACE Forecast Model for Lake Lavon, 1996	East Fork Trinity upstream of Crandall Gage	No	Rainfall-runoff modeling	HEC-1 modeling utilized regional Ct value to compute lag times.
USACE Lower Trinity Reconaissance Study, 1991	Area between Trinity nr Rosser Gage downstream to confluence with Chambers Creek.	Yes	Rainfall-runoff modeling	HEC-1 modeling utilized regional Ct value to compute lag times.

2.4 CURRENTLY EFFECTIVE FEMA FLOWS

Frequency flows that are on the currently effective flood insurance rate maps are developed from various hydrologic methods including rainfall-runoff modeling, statistical hydrology, and regression equations.. A significant portion of the currently effective FEMA flows for the Trinity River and it's associated tributaries, within the Dallas/Fort Worth metropolitan area, was developed by the USACE during the late 1970s into the late 1980s. The USACE primary source for developing the FEMA effective flows was rainfall-runoff modeling and regionalized (Fort Worth District Urban Curve) equations for populating parameters within those models (Rodman).

3 Methodology

The methodology that was used for this basin-wide hydrology study was a multi-layered analysis that calculated frequency flows in the Trinity River Basin through several different methods and compared their results to each other before making final flow recommendations. The purpose of this analysis is to produce a set of frequency flows that are consistent and defendable across the basin.

The current study builds upon the information that was available from the previous hydrology studies by combining detailed data from different models, updating land use data, calibrating the models to multiple recent flood events, and updating statistical analyses to include the most recent flood events.

The multi-layered analysis for the current study of the basin consists of four main components: (1) statistical analysis of the stream gages, (2) rainfall-runoff watershed modeling in the Hydraulic Engineering Center's Hydrologic Modeling System (HEC-HMS), (3) extended period-of-record modeling in RiverWare, and (4) a reservoir study of 8 USACE reservoirs and 1 TRWD reservoir. After completing all of these different types of analyses, their results were then compared to each other and to the existing published frequency flows within the basin. Frequency flow recommendations were then made after consideration of all the known hydrologic information. Each method is summarized in the following sections of this report with additional detail being covered in appendicies A through F.

4 Data Collection

This section describes the data that was collected/reviewed for the hydrologic study effort, including geospatial and climatic information, field observations and previous reports for the Trinity River Basin.

4.1 SPATIAL TOOLS AND REFERENCE

ArcGIS version 10.2.2 (developed by ESRI), together with HEC-GeoHMS version 10.2 were used to process and analyze the data necessary for hydrologic modeling and to generate the sub-basin boundaries.

The geographic projection parameters used for this study are listed below:

- Horizontal Datum: North American Datum 1983 (NAD83);
- Projection: USA Contiguous Albers Equal Area Conic USGS version;
- Vertical Datum: North American Vertical Datum, 1988 (NAVD 88); and
- Linear units: U.S. feet.

4.2 DIGITAL ELEVATION MODEL (DEM)

As part of the Trinity CWMS implementation, 10-meter and 30-meter DEMs were collected from the seamless USGS National Elevation Dataset (NED, accessed January 2013) for the study watershed from the http://seamless.usgs.gov <http://seamless.usgs.gov> website. The elevations of the NED are in meters. The vertical elevation units were converted from meters to feet, and the datasets were projected into the standard map projection.

Where available, high resolution terrain data from different sources (photagrametric data and Lidar data), and different vintages were utilized in the hydraulic modeling used to develop routing information for the HEC-HMS modeling.

4.3 VECTOR AND RASTER GEOSPATIAL DATA

The mapping team member utilized web mapping services and downloaded the USGS hydrologic unit boundaries, USGS stream gages, USGS medium resolution National Hydrography Dataset (NHD), National Inventory of Dams (NID) data, National Levee Database (NLD) levee centerlines as well as general base map layers. Additional vector data were obtained from the ESRI database and used in figures prepared for the final report. Raster Data includes the National Land Cover Database (NLCD) 2011 and 2016 land cover layers and percent imperviousness layers from the http://seamless.usgs.gov website. The 2011 data was available upon study initiation but was superceded with the 2016 data before study completion.

4.4 AERIAL IMAGES

The CWMS team utilized current high resolution imagery from the National Aerial Imagery Program (NAIP) with a horizontal accuracy based upon National Map Accuracy Standards (NMAS), with 1"=200' scale (1-foot imagery) accuracy of +/- 5.0-feet and the 1"=100' scale (0.5-foot imagery) accuracy of +/- 2.5-feet. Digital photos were used to verify watershed boundaries as well as delineate centerlines and other geographic features. In addition, Google Earth, and Bing Maps were also used to locate important geographic features.

4.5 SOIL DATA

Gridded Soil Survey Geographic (SSURGO) datasets were obtained during the Trinity CWMS study. These datasets were used to estimate initial and constant loss rates for the frequency storm events in HEC-HMS and to calculate initial estimates of the Snyder's lag time. The lag times were modified during calibration.

4.6 PRECIPITATION DATA

Historic precipitation data for observed storm events were collected from the NWS gridded precipitation data files. NEXRAD Stage III grids were used for the basin. The NEXRAD Stage III grids are stored in a binary file format called XMRG. The historical XMRG data were processed into hourly precipitation grids in HEC-DSS format using HEC-METVUE. This data was acquired from the NWS West Gulf River Forecasting Center (WGRFC).

Frequency point rainfall depths of various durations and recurrence intervals were collected for the Trinity River basin from National Oceanic and Atmospheric Administration (NOAA) Atlas 14 Volume 11: Precipitation Frequency Atlas of the United States, Texas, published in 2018 (NOAA, 2018). The point rainfall depths varied by county throughout the watershed. A precipitation depth was asssigned to each county located within the Trinity River watershed. The depth was approximately taken from the center of each county. Watershed subbasins were assigned the point rainfall depth for the particular county containing the majority of that subbasins drainage area.. The precipitation values for Texas generally increase from Northwest to Southeast. The 1% annual chance (100-yr) value ranged from 8.3 inches in Archer County to 17.9 inches in Liberty county near the Gulf for the 24-hour duration. Tarrant and Dallas County had values of 9.6 inches and 9.2 inches respectively. The complete list of precipitation values can be found in the Appendix B – Rainfall Runoff Modeling in HEC-HMS. The frequency precipitation depths were utilized as point rainfall depths in the frequency storms for the final HEC-HMS rainfall-runoff model.

4.7 STREAM FLOW DATA

The USGS stream flow gages located in the basin are listed in Table 4.1 below. The table also indicates whether the gage record was used in this study's statistical analysis or in the calibration of the HEC-HMS model. For these gage sites, annual peak flow data and 15-minute stream flow and stage data was collected from the USGS NWIS website.

Table 4.1: USGS Stream Flow Gages in the Trinity Basin

SHEF ID	USGS ID	Location Description	Drainage Area (sq mi)	Used in HEC-HMS Calibration	Included in the Statistical Analysis
JAKT2	08042800	W Fk Trinity Rv nr Jacksboro, TX	683	Yes	Yes
LCJT2	08042820	Lost Creek Reservoir nr Jacksboro, TX	123	Yes	
BPRT2	08043000	Bridgeport Reservoir ab Bridgeport, TX	1,111	Yes	
BCAT2	08043700	Lake Amon G. Carter nr Bowie, TX	100	Yes	
BRPT2	08044000	Big Sandy Ck nr Bridgeport, TX	333	Yes	Yes
BOYT2	08044500	W Fk Trinity Rv nr Boyd, TX	1,725	Yes	Yes
WCRT2	08044800	Walnut Ck at Reno, TX	76	Yes	Yes
EAMT2	08045000	Eagle Mountain Reservoir ab Fort Worth, TX	1,970	Yes	
FLWT2	08045400	Lake Worth ab Fort Worth, TX	2,064	Yes	
WFTT2	08045550	West Fk Trinity Rv at White Settlement Rd, Ft Worth, TX	2,068		
LWFT2	08045800	Lake Weatherford nr Weatherford, TX	109	Yes	
WEAT2	08045850	Clear Fk Trinity Rv nr Weatherford, TX	121		Yes
ADOT2	08045995	Clear Fork Trinity Rv at Kelly Rd nr Aledo, TX	245		Yes
BNBT2	08046500	Benbrook Lake nr Benbrook, TX	429	Yes	
CFBT2	08047000	Clear Fk Trinity Rv nr Benbrook, TX	431		Yes
BMCT2	08047050	Marys Ck at Benbrook, TX	54	Yes	Yes
FWHT2	08047500	Clear Fk Trinity Rv at Ft Worth, TX	518	Yes	Yes
FWOT2	08048000	W Fk Trinity Rv at Ft Worth, TX	2,615	Yes	Yes
BCHT2	08048543	W Fk Trinity Rv at Beach St, Ft Worth, TX	2,685	Yes	Yes
ERMT2	08048970	Village Ck at Everman, TX	85	Yes	Yes
LART2	08049200	Lake Arlington at Arlington, TX	143	Yes	
GPRT2	08049500	W Fk Trinity Rv at Grand Prairie, TX	3,065	Yes	Yes
VNST2	08049580	Mountain Ck nr Venus, TX	26	Yes	Yes
MNFT2	08049700	Walnut Ck nr Mansfield, TX	63	Yes	Yes
JPLT2	08049800	Joe Pool Lake nr Duncanville, TX	232	Yes	
GPET2	08050050	Mountain Ck Lake nr Grand Prairie, TX	295	Yes	
GPAT2	08050100	Mountain Ck at Grand Prairie, TX	298		Yes
GLLT2	08050400	Elm Fk Trinity Rv at Gainesville, TX	174	Yes	Yes
CNVT2	08050800	Timber Ck nr Collinsville, TX	39	Yes	Yes
CVET2	08050840	Range Ck nr Collinsville, TX	29	Yes	Yes
RRLT2	08051100	Ray Roberts Lake nr Aubrey, TX	692	Yes	
PPET2	08051135	Elm Fk Trinity Rv at Greenbelt nr Pilot Point, TX	694		Yes
SGET2	08051500	Clear Ck nr Sanger, TX	295	Yes	Yes
AAYT2	08052700	Little Elm Ck nr Aubrey, TX	76	Yes	Yes
DOET2	08052745	Doe Br at US Hwy 380 nr Prosper, TX	39	Yes	
HIKT2	08052780	Hickory Ck at Denton, TX	129	Yes	

SHEF ID	USGS ID	Location Description	Drainage Area (sq mi)	Used in HEC-HMS Calibration	Included in the Statistical Analysis
LEWT2	08052800	Lewisville Lk nr Lewisville, TX	1,660	Yes	
EFLT2	08053000	Elm Fk Trinity Rv nr Lewisville, TX	1,673		Yes
ICRT2	08053009	Indian Ck at FM 2281, Carrollton, TX	14	Yes	
DCJT2	08053500	Denton Ck nr Justin, TX	400	Yes	Yes
GPVT2	08054500	Grapevine Lk nr Grapevine, TX	695	Yes	
DCGT2	08055000	Denton Ck nr Grapevine, TX	705		Yes
CART2	08055500	Elm Fk Trinity Rv nr Carrollton, TX	2,459	Yes	Yes
EFDT2	08055560	Elm Fk Trinity Rv at Spur 348, Irving, TX	2,537	Yes	
TUCT2	08056500	Turtle Ck at Dallas, TX	8		Yes
DALT2	08057000	Trinity Rv at Dallas, TX	6,106	Yes	Yes
DWRT2	08057200	White Rk Ck at Greenville Ave, Dallas, TX	66	Yes	Yes
TRDT2	08057410	Trinity Rv bl Dallas, TX	6,278	Yes	Yes
---	08057445	Prairie Cr at U.S. Highway 175, Dallas, TX	9		Yes
---	08058900	E Fk Trinity Rv at McKinney, TX	164		
MCKT2	08059000	E Fk Trinity Rv nr McKinney, TX	190	Yes	Yes
ICFT2	08059350	Indian Ck at SH 78 nr Farmersville, TX	104	Yes	
BVWT2	08059400	Sister Grove Ck nr Blue Ridge, TX	83	Yes	Yes
LVNT2	08060500	Lavon Lk nr Lavon, TX	770	Yes	
SHCT2	08061540	Rowlett Ck nr Sachse, TX	120	Yes	Yes
FRHT2	08061550	Lk Ray Hubbard nr Forney, TX	1,071	Yes	
EFHT2	08061551	E Fk Trinity Rv blw Lk Ray Hubbard nr Forney, TX	1,071		
FNYT2	08061750	E Fk Trinity Rv nr Forney, TX	1,118	Yes	Yes
CNLT2	08062000	E Fk Trinity Rv nr Crandall, TX	1,256	Yes	Yes
RSRT2	08062500	Trinity Rv nr Rosser, TX	8,147	Yes	Yes
TDDT2	08062700	Trinity Rv at Trinidad, TX	8,538	Yes	Yes
LTLT2	08062730	New Terrell City Lk nr Terrell, TX	14	Yes	
KMPT2	08062800	Cedar Ck nr Kemp, TX	189	Yes	Yes
KAFT2	08062895	Kings Ck at SH 34 nr Kaufman, TX	224	Yes	
TRNT2	08063010	Cedar Ck Res nr Trinidad, TX	1,007	Yes	
IRNT2	08063048	White Rk Ck at FM 308 nr Irene, TX	66	Yes	
DAWT2	08063050	Navarro Mills Lk nr Dawson, TX	320	Yes	
DWST2	08063100	Richland Ck nr Dawson, TX	333		Yes
WHCT2	08063590	Waxahachie Ck at Waxahachie, TX	60	Yes	Yes
LWWT2	08063600	Lk Waxahachie nr Waxahachie, TX	30	Yes	
BDWT2	08063700	Bardwell Lk nr Ennis, TX	178	Yes	
BRDT2	08063800	Waxahachie Ck nr Bardwell, TX	178		Yes
RCET2	08064100	Chambers Ck nr Rice, TX	807	Yes	Yes
CRHT2	08064510	Halbert Lk nr Corsicana, TX	12	Yes	

SHEF ID	USGS ID	Location Description	Drainage Area (sq mi)	Used in HEC-HMS Calibration	Included in the Statistical Analysis
FFLT2	08064550	Richland-Chambers Res nr Kerens, TX	1,957	Yes	
STET2	08064700	Tehuacana Ck nr Streetman, TX	142	Yes	Yes
LOLT2	08065000	Trinity Rv nr Oakwood, TX	12,833	Yes	Yes
UKOT2	08065200	Upper Keechi Ck nr Oakwood, TX	150	Yes	Yes
CRTT2	08065330	Houston County Lk nr Crockett, TX	49		
CRKT2	08065350	Trinity Rv nr Crockett, TX	13,911	Yes	Yes
MDST2	08065800	Bedias Ck nr Madisonville, TX	321	Yes	Yes
RVRT2	08066000	Trinity Rv at Riverside, TX	15,589		Yes
OALT2	08066170	Kickapoo Ck nr Onalaska, TX	57		Yes
OALT2	08066175	Kickapoo Ck at Onalaska, TX	65		
LVDT2	08066190	Livingston Res nr Goodrich, TX	16,583	Yes	
LIVT2	08066200	Long King Ck at Livingston, TX	141	Yes	Yes
GRIT2	08066250	Trinity Rv nr Goodrich, TX	16,844		Yes
RYET2	08066300	Menard Ck nr Rye, TX	152	Yes	Yes
RMYT2	08066500	Trinity Rv at Romayor, TX	17,186	Yes	Yes
LIBT2	08067000	Trinity Rv at Liberty, TX	17,468	Yes	Yes
MBFT2	08067100	Trinity Rv nr Moss Bluff, TX	17,573		
WCVT2	08067118	Lk Charlotte nr Anahuac, TX	55		
WSVT2	08067252	Trinity Rv at Wallisville, TX	17,796		

4.8 RESERVOIR PHYSICAL DATA

For the eight USACE reservoirs within the Trinity River Basin, the Elevation-Storage tables, spillway rating curves, and outlet structure rating curves were all provided from the USACE Fort Worth District. In some cases, the best available elevation-storage data was obtained from the Texas Water Development Board (TWDB). The TWDB elevation-storage data ends at the top of conservation pool. The elevation-storage data was extended above the top of conservation pool.

Approximately 1,800 NRCS dams and other small dams are located within the Trinity River Basin. Most of these dams were modeled using approximate methods. The effects of these dams were modeled by increasing losses for each subbasin within the model based on the storage capacity of the dams within that watershed. The losses for each subbasin can be found in Appendix B – Rainfall Runoff Modeling in HEC-HMS. Data for these dams was obtained from the National Inventory of Dams (USACE, 2016). 31 dams were modeled in detail as reservoir elements within the HEC-HMS rainfall-runoff model. Table 4.2 summarizes the reservoir data obtained for these dams and their corresponding data sources

Table 4.2: Reservoir Data and Sources for Dams Modeled in Detail

Reservoir / Facility	Data	Source(s)
Lost Creek	Elevation-Storage-Discharge	TRWD
Bridgeport	Elevation-Storage, Elevation-Discharge	TWDB, TRWD
Amon G Carter	Elevation-Storage-Discharge	TRWD
Eagle Mountain	Elevation-Storage, Elevation-Discharge	TWDB, TRWD
Lake Worth	Elevation-Storage-Discharge	TRWD

Reservoir / Facility	Data	Source(s)
Lake Weatherford	Elevation-Storage, Elevation-Discharge	TWDB, HDR Engineering
Benbrook	Elevation-Storage, Elevation-Discharge	TWDB, USACE
Marine Creek	Elevation-Storage-Discharge	TRWD
Lake Arlington	Elevation-Storage, Elevation-Discharge	TWDB, City of Arlington
Joe Pool	Elevation-Storage-Discharge	USACE
Mountain Creek	Elevation-Storage, Elevation-Discharge	USACE and Freese and Nichols, Freese and Nichols
Muenster	Elevation-Storage-Discharge	NRCS
Kiowa	Elevation-Storage, Spillway and Outlet Structures	TWDB, TWDB
Ray Roberts	Elevation-Storage, Elevation-Discharge	TWDB, USACE
SCS 49 dam	Elevation-Storage, Spillway and Outlet Structures	NRCS, NRCS
Lewisville	Elevation-Storage, Elevation-Discharge	TWDB, USACE
Grapevine	Elevation-Storage, Elevation-Discharge	TWDB, USACE
Bachman	Elevation-Storage, Elevation-Discharge	TWDB, TWDB
White Rock	Elevation-Storage, Elevation-Discharge	TWDB, URS/Forrest and Cotton
Lavon	Elevation-Storage, Elevation-Discharge	TWDB, USACE
Ray Hubbard	Elevation-Storage, Elevation-Discharge	TWDB, Forrest and Cotton
New Terrell City	Elevation-Storage, Elevation-Discharge	TWDB, TWDB
Cedar Creek	Elevation-Storage, Elevation-Discharge	TRWD
Lake Waxahachie	Elevation-Storage, Elevation-Discharge	TWDB, Freese and Nichols
Bardwell	Elevation-Storage, Elevation-Discharge	TWDB, USACE
Lake Halbert	Elevation-Storage, Elevation-Discharge	TWDB, TCEQ
Navarro Mills	Elevation-Storage, Elevation-Discharge	TWDB, USACE
Richland-Chambers	Elevation-Storage, Elevation-Discharge	TWDB, USACE
Fairfield	Elevation-Storage, Elevation-Discharge	TWDB, TWDB
Houston County	Elevation-Storage, Elevation-Discharge	TWDB, TWDB
Lake Livingston	Elevation-Storage, Elevation-Discharge	TRA, USACE

4.9 SOFTWARE AND DOCUMENTATION

The following table provides a summary of the significant computer software programs and versions that were used in the the study.

Table 4.3: List of Computer Programs Used

Program	Version	Capability	Developer
RiverWare	7.0.4	Period of Record Reservoir Operation Simulations	CADSWES
ArcGIS	10.2.2	Geographical Information System	ESRI
HEC-DSSVue	2.0.1	Plot, tabulate, edit and manipulate data in HEC-DSS format	HEC
HEC-GeoHMS	10.2	Watershed delineation and generating HEC-HMS input	HEC
HEC-METVUE	2.2.10.2 Beta	Processing and viewing precipitation data	HEC
HEC-HMS	4.2.1, 4.3	Rainfall-runoff simulation	HEC
HEC-RAS	4.1, 5.6	Steady, Unsteady Flow, and 2d (v5.6) Analysis, ModPuls routing	HEC
HEC-SSP	2.1.1	Statistical Software Package	HEC
RMC-RFA	1.0.0	Reservoir Frequency Analysis	RMC
PeakFQ	7.1	Statistical Analysis of Gage Records for Flood Frequency	USGS

5 Statistical Hydrology

Statistical analysis of the observational record (systematic and historical) at USGS streamflow-gaging stations (stream gages) provides an informative means of estimating flood flow frequency. The annual peak streamflow data as part of systematic operation of a stream gage provide the foundation, but additional historical information or anticipated flow contexts also can be used. An annual peak streamflow is defined as the maximum instantaneous streamflow for a stream gage for a given water year, and annual peak streamflow data for USGS stream gages can be acquired through the USGS National Water Information System (NWIS) (USGS, 2017). The statistical analyses are based on water year increments. A water year is the 12 month period October 1 through September 30 designated by the calendar year in which it ends.

For the statistical hydrology portion of the multi-layered analysis, InFRM team members from the USGS analyzed annual peak streamflow gage records for the selected USGS stream gages. These stream gages are important to the InFRM study objectives, and the locations of the stream gages are shown in Figure 5.1 and Figure 5.2. In August of 2017, Hurricane Harvey made landfall on the Texas Gulf Coast and slowly moved northeast. As it did so, it produced 60 inches (in.) of rainfall in some areas, which is approximately 15 in. more than the average annual amount of rainfall for eastern Texas and the Texas Coast (Blake & Zelinsky, 2018). As a result of Hurricane Harvey, four of the gages (Bedias Ck nr Madisonville, Trinity nr Goodrich, Menard Ck at Rye, and Trinity at Liberty) included in the Trinity River basin analysis recorded annual peak streamflow rankings in the top five of all annual peaks for that given station. Therefore, the period of record analyzed at those gages was extended through 2017 to include this exceptional event.

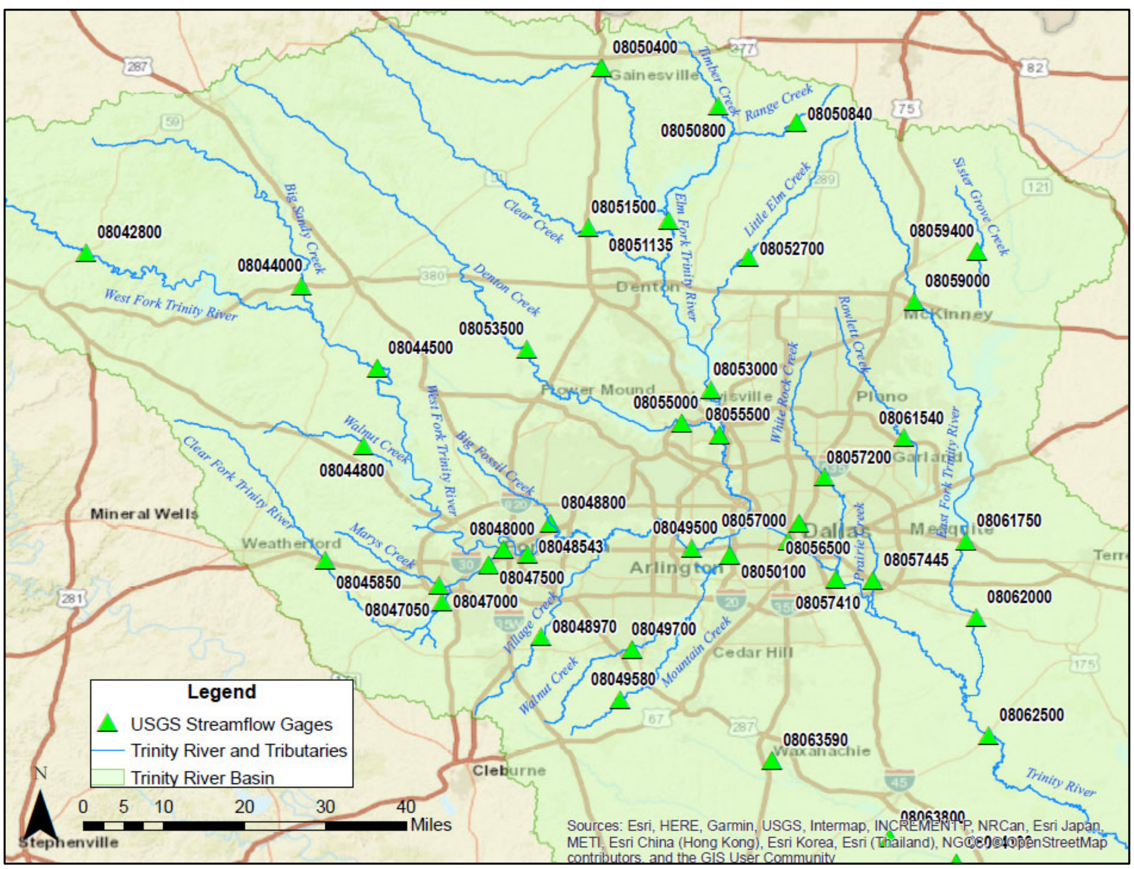


Figure 5.1: Map of USGS Streamflow-Gaging Stations Included in the Statistical Analysis (DFW Detail)

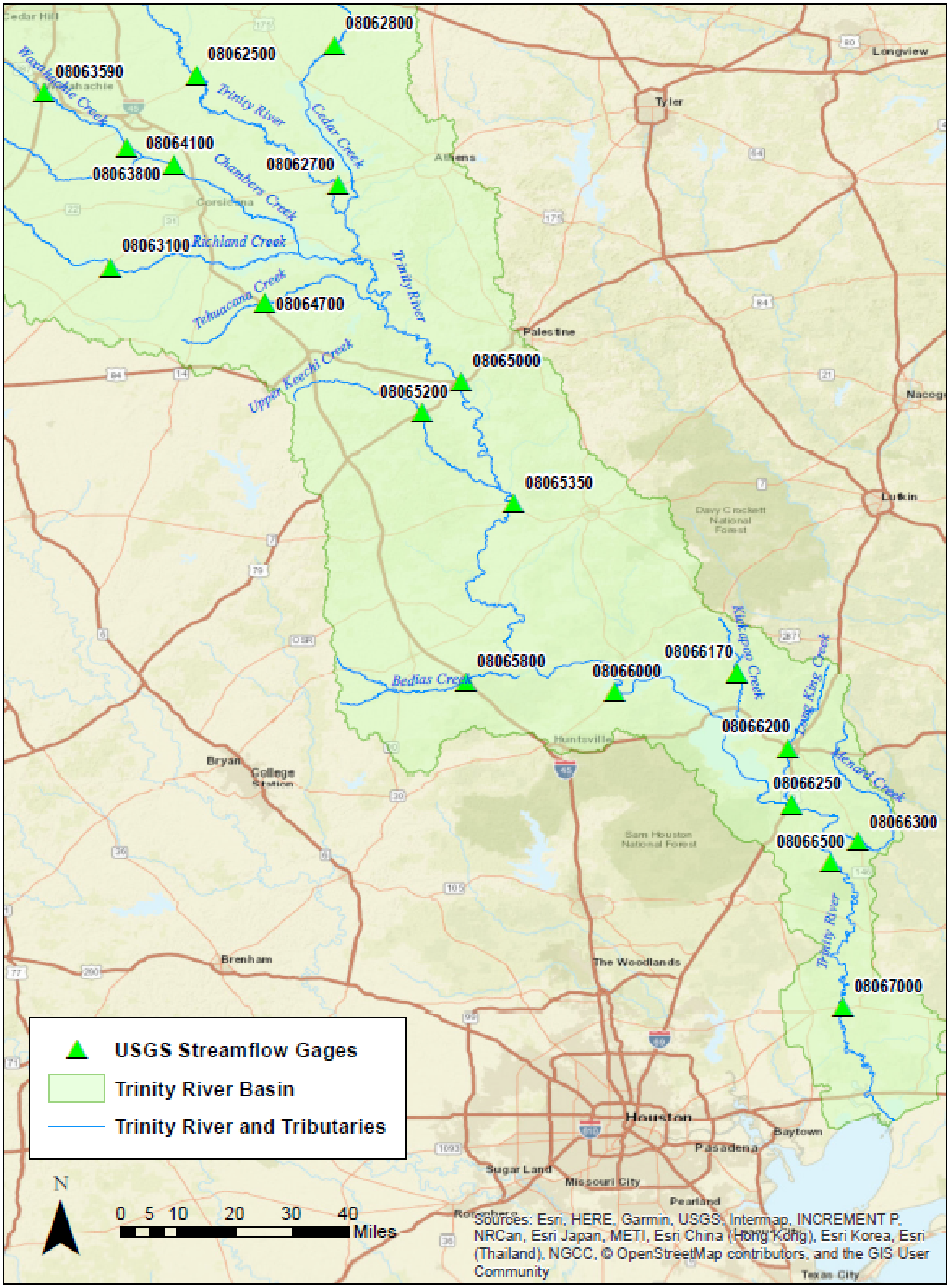


Figure 5.2: Map of USGS Streamflow-Gaging Stations included in the Statistical Analysis (Below DFW)

5.1 STATISTICAL METHODS

The statistical methods involved in this chapter include the fitting of a log-Pearson type III probability distribution (LPIII) to the data. The general purpose of fitting a probability distribution is to provide an objective mechanism to extrapolate to hazard levels (as represented by annual exceedance probabilities and equivalently expressed as annual recurrence interval or recurrence interval measured in years) beyond those represented by the sample size of annual peak streamflow data for a given stream gage. A distribution, such as the LPIII, can be fit by numerous methods, and the logarithms (base-10) of the annual peak streamflow data are most commonly used in practice. The USGS-PeakFQ software version 7.1 (Veilleux et al., 2013; USGS, 2014) provides the foundation for the results of the flood frequency flows which are specified by average annual recurrence intervals computed and extracted from software output at 2, 5, 10, 25, 100, 200, and 500 years and accompanied by the 95-percent confidence limits.

Flood flow frequency analyses were conducted for the stream gages using the annual peak data from the USGS NWIS website (USGS, 2017) with historical information when available and data augmentation when required. The Interagency Advisory Committee on Water Data (IACWD, 1982) describes a Bulletin 17B method (B17B) to conduct the frequency analysis (USGS, 2014), but the statistical frequency analysis performed for the Trinity River Basin is singularly focused on updated guidelines from Bulletin 17C (England et al., 2017).

Wide-spread reservoir construction in the Trinity River basin has occurred and is attested by the USACE National Inventory of Dams. There are almost 1,700 dams listed in the USACE National Inventory of Dams for the entire Trinity River basin. A "major" reservoir is defined only for this chapter as one either with geographic importance, notably large normal capacity, or flood storage capacity. These major reservoirs and their general time of construction/filling serve as points of reference for decision making for time periods analyzed. Eighteen major reservoirs have been built in the entire Trinity River basin: Lake Worth in 1914, Lake Bridgeport in 1931, Eagle Mountain Lake in 1932, Benbrook Lake in 1951, Lake Grapevine in 1952, Lake Lavon in 1953, Lake Lewisville in 1954, Lake Arlington in 1955, Lake Amon Carter in 1956, Lake Weatherford in 1957, Navarro Mills Lake in 1963, Bardwell Lake in 1965, Cedar Creek Reservoir in 1966, Lake Livingston in 1969, Lake Ray Hubbard in 1969, Joe Pool Lake in 1986, Lake Ray Roberts in 1986, and Richland-Chambers in 1987. It is difficult to disaggregate the statistical impact of these reservoirs in a systematic way for most of the stream gages of this study. Further, the primary statistical approach using the USGS-PeakFQ software has no capacity for the cumulative and temporal integration of all of these reservoirs. The analyst is left with decisions on what time periods to analyze, weighing factors such as sample size available for the estimation of rare events through flood flow frequency analyses.

Another complication to be addressed is that periods of record between stream gages are seldom identical. However, in the Trinity River basin this is partially mitigated by the tendency for analyses to be made for "modern times" of streamflow regulation. There is a complex and difficult-to-interpret history of reservoir construction throughout the Trinity River basin. The USACE National Inventory of Dams was used as a reference for data review in consultation with USGS "code 6" (substantial regulated effects anticipated) or "code C" (substantial urban effects anticipated). An effort to somewhat normalize the years of data input into statistical methods amongst the stream gages was made for two primary purposes to (1) foster similar sample sizes yet consult information on timing of reservoir flood-storage capacity, and (2) use historical information to extended record lengths as defendable from nearby stream gage or meteorological data. However, because of wide spread reservoir construction in the Trinity River basin, it is difficult to use all of the historical (outside-of-gaged record) information contained in the USGS Peak-Values File. The details of analysis are further described on a gage-by-gage basis. A code “C” in the database indicates an urban peak. PeakFQ does not distinguish between a code 6 and a code C in its graphical output.

Other statistical techniques used for data evaluation included the Kendall Test. The Kendall’s tau test (Helsel & Hirsch, 2002) was used through the USGS-PeakFQ software to detect for the presence of monotonic trends in the annual peak streamflow data. Kendall’s tau test is a popular statistic for quantifying the presence of monotonic changes in the central tendency of streamflow data in time. The Kendall tau results are listed in Table 1, and only one of the stream gages shows a trend in annual peak streamflow for an alpha at the 0.10 probability significance level.

The use of the expected-moments algorithm (EMA)(England et al., 2017; USGS, 2014) permits sophisticated interpretations of the historical record that are intended to enhance the estimates of peak streamflow, especially for the rare frequency events such as the 100-year streamflow. This type of information is not often used for the analyses described herein because of the complex history of reservoir construction in the basin. Inclusion of historical record interpretations can have the net impact of lowering (decreasing) flood flow frequency estimates for the largest streamflows when they appear as outliers because the largest documented events are assigned lower empirical probabilities when historical information is available. EMA also permits inclusion of nonstandard information such as data censoring. For example, an annual peak might be known to be lower than a specified discharge threshold. EMA can also accommodate time varying discharge thresholds based on assigning a discharge threshold as a "highest since" (a term intrinsic to flood flow frequency analyses) within discrete blocks or intervals of time. This nonstandard information collectively can be thought of as a framework fostering record extension.

Two especially important options of the USGS-PeakFQ software are the choice of a low-outlier threshold and generalized skew, which are technical elements of the statistical analysis. The skew involves the decision as to incorporate a weighting in the analyses between the generalized skew and that computed using the site-specific data. Low outliers (potentially influential low floods, PILFs in USGS-PeakFQ paralance) within a time series of peak streamflow, such as annual peaks that in reality were likely not storm flows or highly localized storm flow, often require removal from the analysis using a form of conditional probability adjustment. To this end, the so-called Multiple Grubbs-Beck low-outlier threshold (MGBT) was used with some cases of user-substituted (manual) override. For location-specific reasons, the analyst manually specified a low-outlier threshold. The settings for low-outlier detection or the results of the MGBT are identified in Section 5 and listed in Table 5.1.

Skew is an expression of the curvature or shape of the LPIII distribution intended to mimic that of the data (Asquith, 2011a,b). The importance of a generalized or regional skew is stressed in IACWD (1982) to mitigate for high sampling variance using typical record lengths available for stream gages. A substantial motivation for a generalized skew is to compensate for inefficient estimation of the product moment skew for highly variable and skewed data such as annual peak streamflow. The generalized skew coefficient is a built-in feature of USGS-PeakFQ but can be overridden by the user. Because of age as well as study objectives for the present (2016) study, the maps of generalized skew for Texas in IACWD (1982) or Judd et al. (1996) are of uncertain applicability for this study. The former reference represents a highly generalized estimate of skew dating from about the late 1970s, the later reference represents a substantially more recent, but still dated, estimate of generalized skew for Texas. Low-outlier thresholds can greatly affect the estimate of skewness; for this study, the station-skew option in USGS-PeakFQ almost exclusively was used. In fact, only for stream gages proximal to Richland-Chambers reservoir were weighted-skew options made; this was deliberate because a very short record station in that major subbasin of the Trinity River was included and holistic treatment for analysis consistency around this reservoir was made. Details are described in Appendix A – Statistical Hydrology. Lastly, and as a general rule, the widespread reservoir construction in the Trinity River basin further complicates skew assessment.

Confidence limits of flood flow frequency can be informative to decision makers. The lower and upper limits of 95-percent confidence intervals were computed for this study. Confidence intervals can be expected to encompass the true value 95 percent of the time (Good & Hardin, 2003, p. 100). The range in these numbers for the lower and upper 95-percent confidence limits increases with the more extreme events. Table 5.1 identifiesl the USGS streamflow gages that were analyzed.

Table 5.1: Summary of Selected U.S. Geological Survey Streamflow-Gaging Stations in the Trinity River Basin

Station number	Station name	Latitude	Longitude	Horizontal datum as reported by NWISWeb public interface	Beginning water year of analyzed annual peak stream-flows	Ending water year of analyzed annual peak stream-flows	Contri-buting drainage area (mi²)	Low-outlier threshold used (ft³/s)	Kendall's Tau of analyzed annual peak streamflows	Kendall's Tau p-value of analyzed annual peak streamflows (--)
08042800	West Fork Trinity River near Jacksboro, Tex.	33.291779	-98.080598	NAD83	1974	2016	683.0	279	-0.014	0.900
08044000	Big Sandy Creek near Bridgeport, Tex.	33.231782	-97.694754	NAD83	1937	2016	333.0	MGBT-0	-0.094	0.247
08044500	West Fork Trinity River near Boyd, Tex.	33.085399	-97.558636	NAD83	1948	2016	1,725.0	MGBT-0	-0.026	0.752
08044800	Walnut Creek at Reno, Tex.	32.945680	-97.583080	NAD83	1993	2016	75.6	MGBT-0	-0.123	0.413
08045850	Clear Fork Trinity River near Weatherford, Tex.	32.740407	-97.651971	NAD83	1981	2016	121.0	MGBT-0	0.029	0.817
08047000	Clear Fork Trinity River near Benbrook, Tex.	32.665133	-97.441964	NAD83	1953	2016	431.0	703	0.076	0.378
08047050	Marys Creek at Benbrook, Tex.	32.695132	-97.447242	NAD83	1999	2016	54.0	MGBT-0	-0.137	0.449
08047500	Clear Fork Trinity River at Fort Worth, Tex.	32.732353	-97.358906	NAD83	1953	2016	518.0	7,690	0.353	<0.001
08048000	West Fork Trinity River at Fort Worth, Tex.	32.760963	-97.332517	NAD83	1933	2016	2,615.0	MGBT-0	0.184	0.013
08048543	West Fork Trinity River at Beach Street, Fort Worth, Tex.	32.751797	-97.289460	NAD83	1977	2016	2,685.0	0	0.104	0.351
08048800	Big Fossil Creek at Haltom City, Tex.	32.807351	-97.248626	NAD83	1960	2016	52.8	MGBT-0	-0.238	0.235
08048970	Village Creek at Everman, Tex.	32.603469	-97.265014	NAD83	1990	2016	84.5	5,260	0.043	0.770
08049500	West Fork Trinity River at Grand Prairie, Tex.	32.762500	-96.994444	NAD83	1933	2016	3,065.0	MGBT-0	0.155	0.037
08049580	Mountain Creek near Venus, Tex.	32.490972	-97.123065	NAD83	1986	2016	25.5	1,400	0.082	0.529
08049700	Walnut Creek near Mansfield, Tex.	32.580970	-97.101953	NAD83	1961	2016	62.8	1,160	0.128	0.166
08050100	Mountain Creek at Grand Prairie, Tex.	32.749861	-96.926111	NAD83	1986	2016	298.0	7,000	0.017	0.905
08050400	Elm Fork Trinity River at Gainesville, Tex.	33.624275	-97.156402	NAD83	1986	2016	174.0	MGBT-0	-0.131	0.308
08050800	Timber Creek near Collinsville, Tex.	33.554554	-96.947227	NAD83	1986	2016	38.8	MGBT-0	-0.112	0.386
08050840	Range Creek near Collinsville, Tex.	33.526220	-96.807219	NAD83	1993	2016	29.2	438	-0.069	0.655
08051135	Elm Fork Trinity River at Greenbelt near Pilot Point, Tex.	33.349722	-97.035556	NAD83	2010	2016	694.0	MGBT-0	0.333	0.368

Station number	Station name	Latitude	Longitude	Horizontal datum as reported by NWISWeb public interface	Beginning water year of analyzed annual peak stream-flows	Ending water year of analyzed annual peak stream-flows	Contri-buting drainage area (mi²)	Low-outlier threshold used (ft³/s)	Kendall's Tau of analyzed annual peak streamflows	Kendall's Tau p-value of analyzed annual peak streamflows (--)
08051500	Clear Creek near Sanger, Tex.	33.336227	-97.179459	NAD83	1949	2016	295.0	3,130	-0.039	0.645
08052700	Little Elm Creek near Aubrey, Tex.	33.283450	-96.892781	NAD83	1957	2016	75.5	MGBT-0	-0.087	0.342
08053000	Elm Fork Trinity River near Lewisville, Tex.	33.045677	-96.961117	NAD83	1986	2016	1,673.0	MGBT-0	-0.080	0.541
08053500	Denton Creek near Justin, Tex.	33.119010	-97.290573	NAD83	1950	2016	400.0	MGBT-0	-0.023	0.791
08055000	Denton Creek near Grapevine, Tex.	32.987068	-97.012786	NAD83	1953	2016	705.0	900	0.135	0.165
08055500	Elm Fork Trinity River near Carrollton, Tex.	32.965957	-96.944450	NAD83	1955	2016	2,459.0	4,000	0.047	0.593
08056500	Turtle Creek at Dallas, Tex.	32.807351	-96.802501	NAD83	1947	1991	8.0	MGBT-0	0.285	0.005
08057000	Trinity River at Dallas, Tex.	32.774852	-96.821946	NAD83	1955	2016	6,106.0	19,600	0.161	0.066
08057200	White Rk Creek at Greenville Avenue, Dallas, Tex.	32.889292	-96.756666	NAD83	1962	2016	66.4	7,700	-0.044	0.655
08057410	Trinity River below Dallas, Tex.	32.707631	-96.735832	NAD83	1957	2016	6,278.0	MGBT-0	0.140	0.125
08057445	Prairie Creek at U.S. Highway 175, Dallas, Tex.	32.704853	-96.669996	NAD83	1976	2011	9.0	800	0.218	0.083
08059000	East Fork Trinity River near McKinney, Tex.	33.203727	-96.595824	NAD83	1950	2016	190.0	MGBT-0	-0.052	0.685
08059400	Sister Grove Creek near Blue Ridge, Tex.	33.294558	-96.483597	NAD83	1976	2016	83.1	MGBT-0	0.191	0.080
08061540	Rowlett Creek near Sachse, Tex.	32.959844	-96.614438	NAD83	1969	2016	120.0	MGBT-0	0.100	0.319
08061750	East Fork Trinity River near Forney, Tex.	32.774295	-96.503599	NAD83	1974	2016	1,118.0	5,140	0.010	0.933
08062000	East Fork Trinity River near Crandall, Tex.	32.638744	-96.485265	NAD83	1954	2016	1,256.0	4,500	0.109	0.209
08062500	Trinity River near Rosser, Tex.	32.426530	-96.463042	NAD83	1954	2016	8,147.0	MGBT-0	0.187	0.030
08062700	Trinity River at Trinidad, Tex.	32.147653	-96.102471	NAD83	1965	2016	8,538.0	20,000	-0.006	0.956
08062800	Cedar Creek near Kemp, Tex.	32.503471	-96.112751	NAD83	1970	2016	189.0	MGBT-0	-0.089	0.486
08063100	Richland Creek near Dawson, Tex.	31.938491	-96.681379	NAD83	1963	2016	333.0	718	0.122	0.194

Station number	Station name	Latitude	Longitude	Horizontal datum as reported by NWISWeb public interface	Beginning water year of analyzed annual peak stream-flows	Ending water year of analyzed annual peak stream-flows	Contri-buting drainage area (mi^2)	Low-outlier threshold used (ft^3/s)	Kendall's Tau of analyzed annual peak streamflows	Kendall's Tau p-value of analyzed annual peak streamflows (--)
08063590	Waxahachie Creek at Waxahachie, Tex.	32.382222	-96.850556	NAD83	2009	2016	60.4	MGBT-0	-0.250	0.454
08063800	Waxahachie Creek near Bardwell, Tex.	32.243481	-96.640268	NAD83	1964	2016	178.0	881	-0.009	0.927
08064100	Chambers Creek near Rice, Tex.	32.198482	-96.520264	NAD83	1984	2016	807.0	MGBT-0	0.023	0.865
08064700	Tehuacana Creek near Streetman, Tex.	31.848496	-96.289976	NAD83	1969	2016	142.0	2,000	0.195	0.052
08065000	Trinity River near Oakwood, Tex.	31.648506	-95.789403	NAD83	1924	2016	12,833.0	20,000	-0.009	0.897
08065200	Upper Keechi Creek near Oakwood, Tex.	31.569896	-95.888294	NAD83	1962	2016	150.0	362	-0.028	0.766
08065350	Trinity River near Crockett, Tex.	31.338513	-95.656341	NAD83	1942	2016	13,911.0	10,000	0.025	0.794
08065800	Bedias Creek near Madisonville, Tex.	30.884722	-95.777778	NAD83	1922	2017	321.0	937	-0.001	1.000
08066000	Trinity River at Riverside, Tex.	30.859355	-95.398830	NAD83	1903	1968	15,589.0	MGBT-0	-0.037	0.662
08066170	Kickapoo Creek near Onalaska, Tex.	30.907132	-95.088547	NAD83	1942	2016	57.0	1,090	0.125	0.219
08066200	Long King Creek at Livingston, Tex.	30.716306	-94.958824	NAD83	1942	2016	141.0	1,540	0.161	0.088
08066250	Trinity River near Goodrich, Tex.	30.572145	-94.948822	NAD83	1903	2017	16,844.0	31,600	0.078	0.416
08066300	Menard Creek near Rye, Tex.	30.481389	-94.779722	NAD83	1966	2017	152.0	915	0.128	0.182
08066500	Trinity River at Romayor, Tex.	30.425207	-94.850762	NAD83	1903	2016	17,186.0	21,300	0.107	0.129
08067000	Trinity River at Liberty, Tex.	30.057715	-94.818257	NAD83	1903	2017	17,468.0	24,300	0.060	0.446

5.2 STREAM GAGE DATA AND STATISTICAL FLOOD FLOW FREQUENCY RESULTS

This section presents the results of the statistical analysis of the annual peak streamflow data at each analyzed stream gage. Statistical flow frequency estimates, along with associated uncertainty intervals, are presented in tabular format for the complete list of streamflow gages. Examples of graphical results are presented for 2 gages. Graphical results for the complete list of streamflow gages can be found in Appendix A – Statistical Hydrology. Tables of flood flow frequency values with attendant confidence limits are listed in Table 2 (located at the end of the section). This table contains the preferred values for the statistical analysis computed using USGS-PeakFQ software with EMA-LPIII methods.

In this chapter, some specific terms are used for specific reference to periods of available annual peak streamflow values. The term "gaged record" refers to the total number of years for which the gage was operational and annual peaks were recorded. This does not reflect historical record, which are peaks outside gage operation. The term, "systematic record" refers to the years within the gaged record that were used in the USGS-PeakFQ analysis. Historical record often refers to large and notable floods in the area later represented by an operational stream gage. These floods are often recorded by people living in the area before the installation of the gage. The term "inferred historical record" refers to years in which the peak streamflow thresholds for EMA were inferred using outside information (such as precipitation data or peaks from a nearby gage that is equivalent). A few other terms are needed as they are used for specific purposes. The use of "systematic record" is consistent with parlance inside USGS-PeakFQ software output files. Lastly, the wording "period of record" is inherently mutable and dependent hereinafter on context.

Record length or the number of peaks and historical periods included in flood flow frequency analyses has a substantial impact on inference of flood potential. Short record lengths, which are defined herein as less than 20 years, imply greater error in flood flow frequency estimates than moderate record lengths, which are defined herein as less than 30 years.

08048000 West Fork Trinity River at Fort Worth, Texas

The gage record for the West Fork Trinity River at Fort Worth is 1921–2016. The systematic record is 1933–2016; thus, peaks for 1921–1932 are not used in the analysis. The 1949 peak streamflow of 64,300 ft^3/s at a stage of 25.91 ft is the maximum peak for the systematic record. All of the peaks at the site (1921–2016) are flagged with code 6 in the USGS Peak-Values File), but manual intervention was required to remove the code for the first two peaks so that the USGS-PeakFQ software would operate. This does not affect the statistical analysis—only the visual depiction of the input data. Three major reservoirs have been built upstream of the gage: Bridgeport Lake in 1931, Eagle Mountain Lake in 1932, and Benbrook Lake in 1953. The peaks for 1922–1932 are not used because of the construction of Eagle Mountain Lake. The data as set up in the statistical frequency analysis are shown in Figure 5.3. The Kendall's Tau for monotonic trend is statistically significant (alpha = 0.1;Table 5.1) and shows an upward trend (p-value = 0.013), and this is seen by visual inspection of the data. This might be indicative of watershed urbanization.

The flood flow frequency for the West Fork Trinity River at Fort Worth is shown in Figure 5.4. No low outliers were detected by the Multiple Grubbs-Beck outlier test. In general, the flood flow frequency curve looks reliable to the inputted data. However, this conclusion is weakened by the upward trend in streamflow for the period analyzed. The largest peak (1949) predates Benbrook Lake. This peak plots well above the fitted frequency curve. It is outside the scope of these data to provide further inference of the 1949 peak.

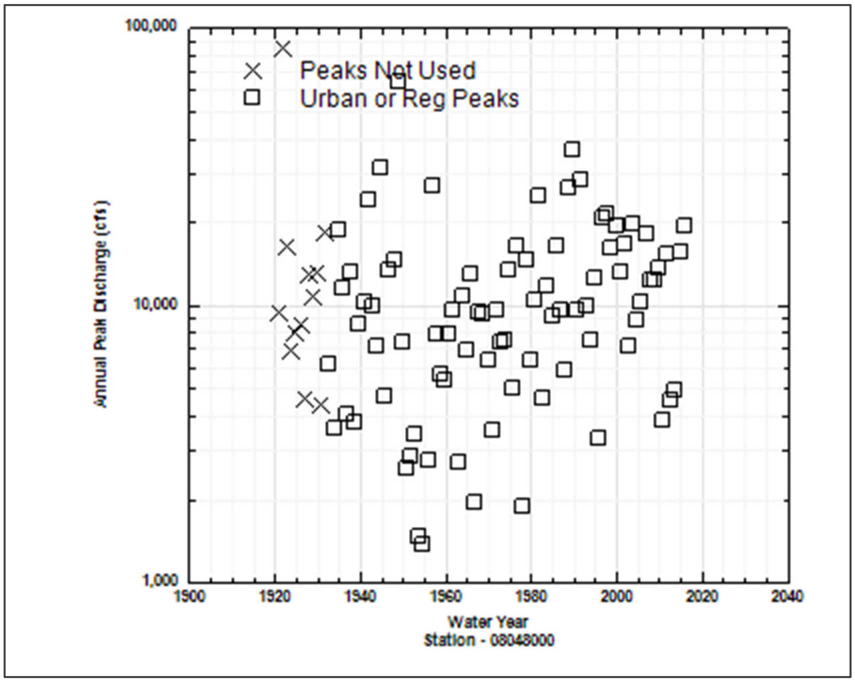


Figure 5.3: Annual Peak Streamflow Data for Station 08048000 West Fork Trinity River at Fort Worth

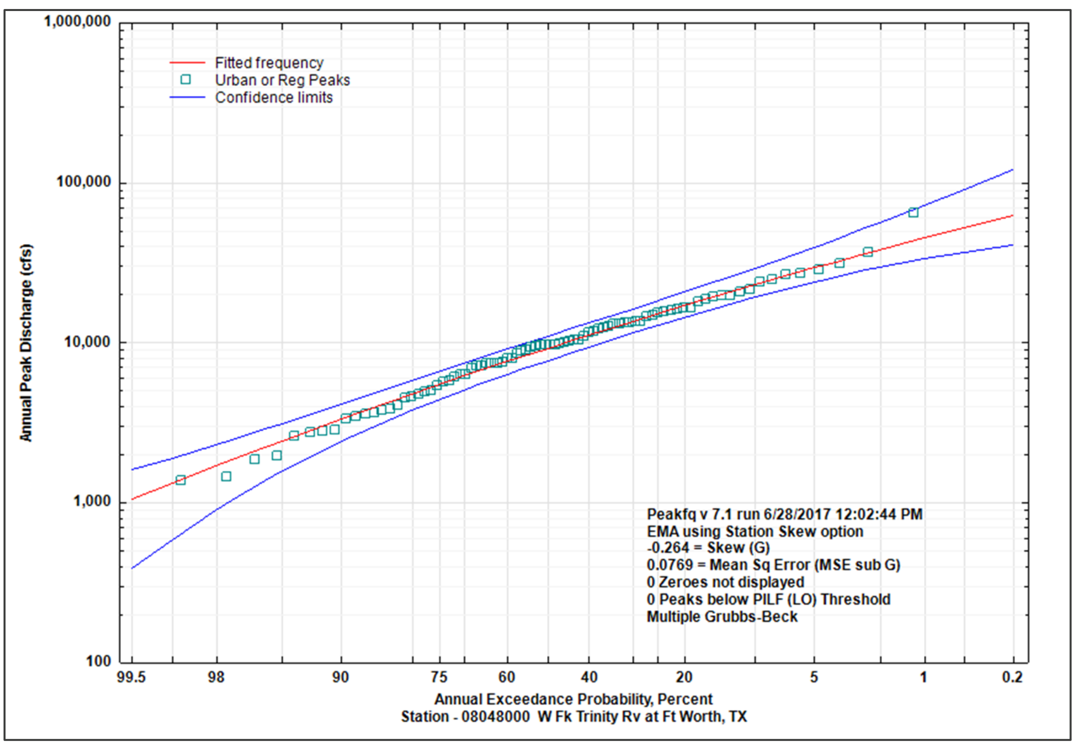


Figure 5.4: Flood Frequency Curve for Station 08048000 West Fork Trinity River at Fort Worth

08057000 Trinity River at Dallas, Texas

The gage record for Trinity River at Dallas is 1904–2016. The systematic record is 1955–2016 thus peaks for 1904–1954 are not used in the analysis. The 1990 peak streamflow of 82,300 ft^3/s at a stage of 47.10 ft is the peak for the systematic record. There is a very large peak in 1908 of 184,000 ft^3/s at a stage of 52.6 ft but is outside of the systematic record. Eleven major reservoirs have been built upstream of the gage: Lake Worth in 1914, Lake Bridgeport in 1931, Eagle Mountain Lake in 1932, Benbrook Lake in 1951, Lake Grapevine in 1952, Lake Lewisville in 1954, Lake Arlington in 1955, Lake Amon Carter in 1956, Lake Weatherford in 1957, Joe Pool Lake in 1986, and Lake Ray Roberts in 1986. It is difficult to disaggregate this complex history, but in short, the peaks from 1904–1954 are not used because the construction of the Lake Lewisville dam. The data as set up for statistical frequency analysis are shown in Figure 5.5. The Kendall's Tau for monotonic trend is statistically significant (alpha = 0.1; Table 5.1) and shows an upward trend (p-value = 0.066), and this is seen by visual inspection of the data. This might be indicative of watershed urbanization. It is possible that the effects of Joe Pool Lake and Lake Ray Roberts in 1986 can be seen from that year onward, yet the largest peak in the systematic record was in 1990.

The flood flow frequency for Trinity River at Dallas is shown in Figure 5.6. The multiple Grubbs-Beck outlier test does an acceptable job identifying low outliers. In general, the flood flow frequency curve looks reliable to the inputted data. However, it is possible that the largest peaks are breaking away from the fitted distribution. The flat regions of the empirical data at about 13,000 ft^3/s and again 30,000 ft^3/s suggest some mixed population effects.

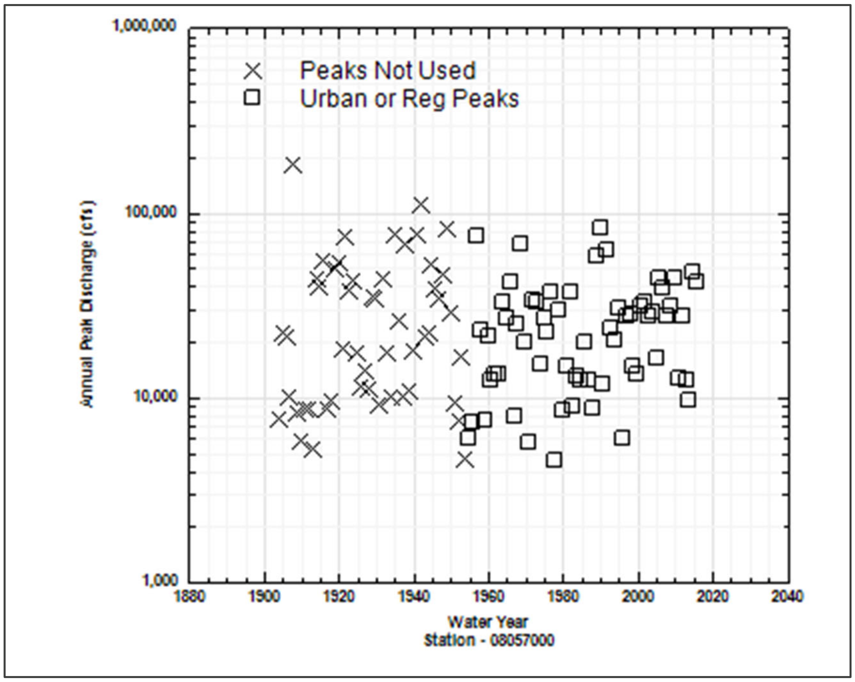


Figure 5.5: Annual Peak Streamflow Data for Station 08057000 Trinity River at Dallas

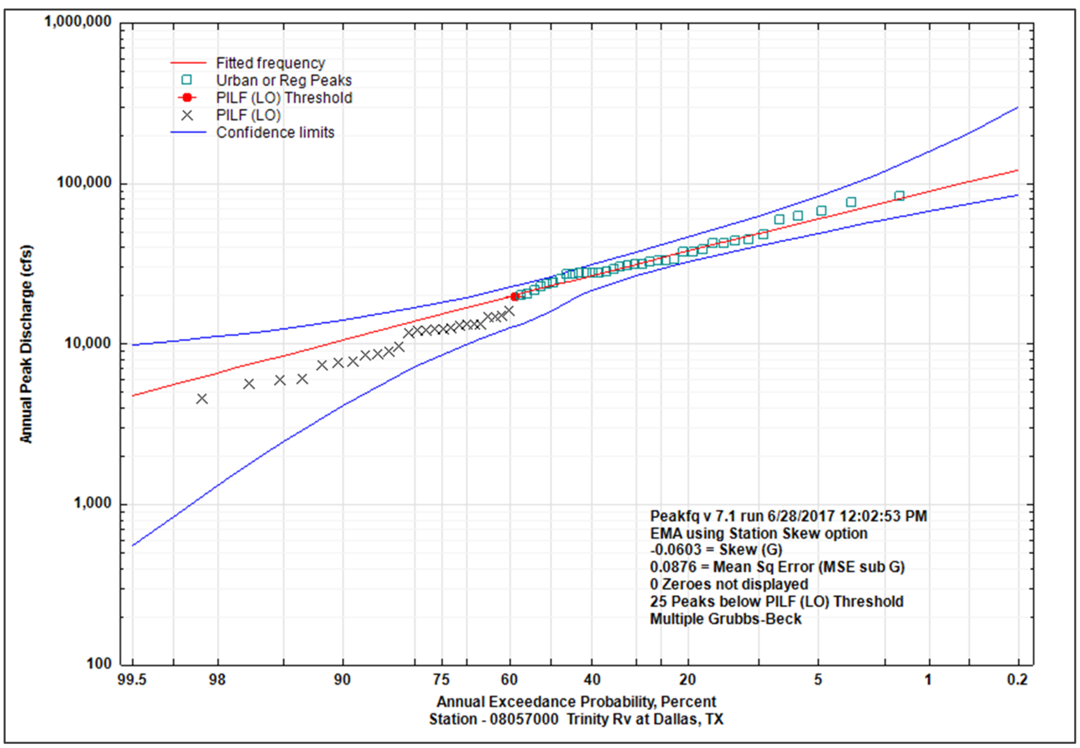


Figure 5.6: Flood Flow Frequency Curve for Station 08057000 Trinity River at Dallas

Table 5.2: Statistically Estimated Annual Flood Flow Frequency Results for Selected U.S Geological Survey Streamflow-Gaging Stations in the Trinity River Basin based on the USGS-PeakFQ EMA-LPIII Computations

Station number and name	Peak-streamflow frequency by corresponding average return period (recurrence interval) in years							
	2 year (ft^3/s)	5 year (ft^3/s)	10 year (ft^3/s)	25 year (ft^3/s)	50 year (ft^3/s)	100 year (ft^3/s)	200 year (ft^3/s)	500 year (ft^3/s)
08042800 West Fork Trinity River near Jacksboro, Tex.								
Lower 95%-CI	1,347	3,936	6,904	12,280	17,510	23,800	31,180	42,670
Estimate	**2,049**	**6,165**	**11,310**	**22,110**	**34,550**	**52,080**	**76,390**	**122,700**
Upper 95%-CI	3,142	10,820	24,850	82,070	220,700	562,100	1,245,000	3,539,000
08044000 Big Sandy Creek near Bridgeport, Tex.								
Lower 95%-CI	2,112	6,163	10,490	17,870	24,590	32,180	40,540	52,690
Estimate	**2,926**	**8,598**	**15,080**	**27,440**	**40,360**	**57,090**	**78,390**	**115,100**
Upper 95%-CI	4,051	12,470	24,120	53,860	95,250	163,800	275,500	533,300
08044500 West Fork Trinity River near Boyd, Tex.								
Lower 95%-CI	2,407	6,547	11,020	18,910	26,500	35,620	46,410	63,500
Estimate	**3,262**	**9,049**	**15,870**	**29,530**	**44,640**	**65,280**	**93,070**	**144,300**
Upper 95%-CI	4,427	13,430	27,240	67,870	134,400	264,100	514,700	1,230,000
08044800 Walnut Creek at Reno, Tex.								
Lower 95%-CI	1,948	5,541	9,197	13,410	15,150	16,000	16,370	16,440
Estimate	**3,632**	**9,727**	**15,210**	**23,330**	**29,990**	**36,970**	**44,190**	**53,970**
Upper 95%-CI	6,629	16,860	32,380	63,260	95,780	142,700	211,500	354,600
08045850 Clear Fork Trinity River near Weatherford, Tex.								
Lower 95%-CI	415	1,036	1,626	2,541	3,300	4,092	4,903	5,993
Estimate	**615**	**1,541**	**2,487**	**4,141**	**5,754**	**7,734**	**10,140**	**14,060**
Upper 95%-CI	913	2,497	4,763	11,030	20,310	36,620	65,010	136,800
08047000 Clear Fork Trinity River near Benbrook, Tex.								
Lower 95%-CI	732	2,196	3,100	4,163	4,822	5,348	5,757	6,165
Estimate	**1,261**	**2,846**	**3,977**	**5,343**	**6,266**	**7,096**	**7,836**	**8,685**
Upper 95%-CI	1,658	3,743	5,488	8,187	10,290	12,330	14,410	17,360
08047050 Marys Creek at Benbrook, Tex.								
Lower 95%-CI	2,045	5,934	9,942	16,400	21,550	26,620	31,460	37,400
Estimate	**3,977**	**11,270**	**19,160**	**33,430**	**47,630**	**65,250**	**86,780**	**122,100**
Upper 95%-CI	7,645	25,380	59,390	181,500	400,600	842,000	1,743,000	4,324,000
08047500 Clear Fork Trinity River at Fort Worth, Tex.								
Lower 95%-CI	4,396	10,920	13,710	16,260	17,840	19,170	20,310	21,560
Estimate	**7,897**	**12,920**	**15,950**	**19,320**	**21,510**	**23,450**	**25,170**	**27,150**
Upper 95%-CI	9,124	15,430	20,780	33,550	42,250	51,450	60,350	71,870
08048000 West Fork Trinity River at Fort Worth, Tex.								
Lower 95%-CI	7,690	14,270	19,150	25,310	29,520	33,280	36,660	40,600
Estimate	**9,194**	**16,980**	**22,980**	**31,290**	**37,920**	**44,850**	**52,100**	**62,140**
Upper 95%-CI	10,990	20,470	28,950	43,110	56,190	71,620	89,880	119,300

Table 5.2: Statistically Estimated Annual Flood Flow Frequency Results for Selected U.S Geological Survey Streamflow-Gaging Stations in the Trinity River Basin based on the USGS-PeakFQ EMA-LPIII Computations

Station number and name	Peak-streamflow frequency by corresponding average return period (recurrence interval) in years							
	2 year (ft^3/s)	5 year (ft^3/s)	10 year (ft^3/s)	25 year (ft^3/s)	50 year (ft^3/s)	100 year (ft^3/s)	200 year (ft^3/s)	500 year (ft^3/s)
08048543 West Fork Trinity River at Beach Street, Fort Worth, Tex.								
Lower 95%-CI	9,511	16,690	21,930	28,620	33,330	37,670	41,650	46,430
Estimate	**12,000**	**21,030**	**27,990**	**37,780**	**45,720**	**54,180**	**63,190**	**75,980**
Upper 95%-CI	15,120	27,520	39,920	64,130	89,700	123,300	167,400	247,900
08048800 Big Fossil Creek at Haltom City, Tex.								
Lower 95%-CI	4,295	8,745	12,530	16,730	18,350	19,120	19,380	19,380
Estimate	**7,449**	**14,390**	**19,450**	**26,010**	**30,870**	**35,630**	**40,300**	**46,290**
Upper 95%-CI	12,350	23,540	40,780	71,110	98,010	133,400	182,100	276,700
08048970 Village Creek at Everman, Tex.								
Lower 95%-CI	3,311	9,307	11,590	13,200	13,860	14,270	14,510	14,700
Estimate	**7,723**	**11,770**	**13,630**	**15,220**	**16,010**	**16,570**	**16,970**	**17,320**
Upper 95%-CI	9,513	15,100	22,460	27,830	31,160	34,350	37,460	41,350
08049500 West Fork Trinity River at Grand Prairie, Tex.								
Lower 95%-CI	7,968	15,030	20,970	29,740	37,090	45,070	53,730	66,270
Estimate	**9,484**	**18,130**	**25,960**	**38,700**	**50,530**	**64,630**	**81,350**	**108,200**
Upper 95%-CI	11,300	22,720	35,450	62,870	96,450	147,100	222,800	382,800
08049580 Mountain Creek near Venus, Tex.								
Lower 95%-CI	2,316	4,448	6,116	8,407	10,150	11,860	13,520	15,640
Estimate	**3,140**	**6,047**	**8,498**	**12,190**	**15,380**	**18,940**	**22,910**	**28,820**
Upper 95%-CI	4,294	8,841	14,140	27,940	50,070	80,830	124,100	216,500
08049700 Walnut Creek near Mansfield, Tex.								
Lower 95%-CI	2,895	5,686	7,853	10,750	12,860	14,860	16,720	19,000
Estimate	**3,677**	**7,212**	**10,100**	**14,310**	**17,820**	**21,610**	**25,700**	**31,570**
Upper 95%-CI	4,662	9,374	13,990	23,180	33,570	48,030	68,060	107,000
08050100 Mountain Creek at Grand Prairie, Tex.								
Lower 95%-CI	7,383	10,590	12,200	14,040	15,260	16,350	17,330	18,490
Estimate	**8,937**	**12,150**	**14,180**	**16,650**	**18,440**	**20,170**	**21,870**	**24,090**
Upper 95%-CI	10,310	14,490	17,750	23,080	28,300	35,080	43,930	54,820
08050400 Elm Fork Trinity River at Gainesville, Tex.								
Lower 95%-CI	6,439	12,440	17,310	24,090	29,330	34,610	39,890	46,840
Estimate	**8,730**	**16,970**	**24,170**	**35,410**	**45,430**	**56,930**	**70,100**	**90,370**
Upper 95%-CI	11,860	25,170	41,510	81,460	136,300	226,200	373,900	666,400
08050800 Timber Creek near Collinsville, Tex.								
Lower 95%-CI	714	2,852	5,473	9,820	12,920	15,550	17,690	19,890
Estimate	**1,409**	**5,382**	**10,260**	**19,590**	**29,110**	**40,970**	**55,380**	**78,610**
Upper 95%-CI	2,742	10,730	25,410	68,960	130,500	235,900	416,800	869,300

Table 5.2: Statistically Estimated Annual Flood Flow Frequency Results for Selected U.S Geological Survey Streamflow-Gaging Stations in the Trinity River Basin based on the USGS-PeakFQ EMA-LPIII Computations

Station number and name	Peak-streamflow frequency by corresponding average return period (recurrence interval) in years							
	2 year (ft^3/s)	5 year (ft^3/s)	10 year (ft^3/s)	25 year (ft^3/s)	50 year (ft^3/s)	100 year (ft^3/s)	200 year (ft^3/s)	500 year (ft^3/s)
08050840 Range Creek near Collinsville, Tex.								
Lower 95%-CI	1,413	3,692	6,002	9,771	13,060	16,630	20,410	25,690
Estimate	**2,346**	**6,228**	**10,460**	**18,290**	**26,340**	**36,650**	**49,680**	**72,010**
Upper 95%-CI	3,967	12,260	27,070	90,360	225,700	456,400	923,500	2,321,000
08051135 Elm Fork Trinity River at Greenbelt near Pilot Point, Tex.								
Lower 95%-CI	139	757	1,768	4,098	6,671	9,940	13,860	20,080
Estimate	**744**	**3,684**	**8,651**	**21,790**	**39,880**	**69,040**	**114,500**	**212,700**
Upper 95%-CI	4,355	48,900	300,900	3,376,000	10,930,000	35,840,000	120,800,000	599,300,000
08051500 Clear Creek near Sanger, Tex.								
Lower 95%-CI	4,415	9,071	13,210	19,560	24,990	30,920	37,300	46,410
Estimate	**5,488**	**11,560**	**17,390**	**27,250**	**36,720**	**48,280**	**62,300**	**85,330**
Upper 95%-CI	6,932	15,520	25,690	52,110	95,600	184,400	307,800	604,200
08052700 Little Elm Creek near Aubrey, Tex.								
Lower 95%-CI	2,278	5,240	7,877	11,770	14,880	18,030	21,190	25,340
Estimate	**3,031**	**6,986**	**10,730**	**16,880**	**22,560**	**29,220**	**36,960**	**49,050**
Upper 95%-CI	4,030	9,717	16,480	31,480	49,530	75,950	114,200	191,700
08053000 Elm Fork Trinity River near Lewisville, Tex.								
Lower 95%-CI	2,544	4,976	6,940	9,649	11,700	13,720	15,690	18,210
Estimate	**3,475**	**6,817**	**9,706**	**14,160**	**18,070**	**22,520**	**27,550**	**35,190**
Upper 95%-CI	4,749	10,080	16,520	31,770	51,580	82,560	131,000	232,700
08053500 Denton Creek near Justin, Tex.								
Lower 95%-CI	3,285	8,201	12,680	19,240	24,240	29,080	33,670	39,330
Estimate	**4,413**	**10,970**	**17,260**	**27,500**	**36,820**	**47,580**	**59,860**	**78,570**
Upper 95%-CI	5,919	15,020	25,570	47,720	72,700	107,300	154,800	245,200
08055000 Denton Creek near Grapevine, Tex.								
Lower 95%-CI	1,311	2,305	3,190	4,503	5,611	6,815	8,113	9,988
Estimate	**1,590**	**2,934**	**4,188**	**6,295**	**8,320**	**10,810**	**13,850**	**18,940**
Upper 95%-CI	1,993	3,977	6,492	14,470	28,120	48,540	84,280	174,800
08055500 Elm Fork Trinity River near Carrollton, Tex.								
Lower 95%-CI	5,311	8,651	11,490	15,570	18,890	22,420	26,180	31,500
Estimate	**6,157**	**10,450**	**14,230**	**20,280**	**25,870**	**32,520**	**40,410**	**53,140**
Upper 95%-CI	7,345	13,250	20,050	38,670	67,790	107,800	171,700	319,300
08056500 Turtle Creek at Dallas, Tex.								
Lower 95%-CI	2,647	4,068	4,998	6,078	6,757	7,326	7,807	8,337
Estimate	**3,125**	**4,780**	**5,903**	**7,332**	**8,396**	**9,456**	**10,520**	**11,930**
Upper 95%-CI	3,685	5,725	7,462	10,270	12,710	15,470	18,630	23,580

Table 5.2: Statistically Estimated Annual Flood Flow Frequency Results for Selected U.S Geological Survey Streamflow-Gaging Stations in the Trinity River Basin based on the USGS-PeakFQ EMA-LPIII Computations

Station number and name	Peak-streamflow frequency by corresponding average return period (recurrence interval) in years							
	2 year (ft^3/s)	5 year (ft^3/s)	10 year (ft^3/s)	25 year (ft^3/s)	50 year (ft^3/s)	100 year (ft^3/s)	200 year (ft^3/s)	500 year (ft^3/s)
08057000 Trinity River at Dallas, Tex.								
Lower 95%-CI	15,730	32,060	40,390	51,060	59,030	66,880	74,580	84,520
Estimate	**22,770**	**37,420**	**48,350**	**63,390**	**75,400**	**88,060**	**101,400**	**120,200**
Upper 95%-CI	26,200	45,770	62,360	90,350	118,300	155,000	204,200	297,800
08057200 White Rk Creek at Greenville Avenue, Dallas, Tex.								
Lower 95%-CI	13,410	21,530	26,460	31,970	35,220	37,770	39,770	41,790
Estimate	**16,200**	**25,450**	**31,220**	**37,950**	**42,540**	**46,780**	**50,720**	**55,530**
Upper 95%-CI	19,330	30,150	37,940	50,030	60,730	72,830	86,770	109,000
08057410 Trinity River below Dallas, Tex.								
Lower 95%-CI	16,800	28,770	37,470	48,700	56,790	64,480	71,800	80,940
Estimate	**20,190**	**34,650**	**45,830**	**61,600**	**74,480**	**88,280**	**103,100**	**124,300**
Upper 95%-CI	24,260	42,960	60,670	92,790	125,300	166,400	218,500	308,900
08057445 Prairie Creek at U.S. Highway 175, Dallas, Tex.								
Lower 95%-CI	1,561	2,501	3,190	4,085	4,747	5,391	6,024	6,839
Estimate	**1,934**	**3,134**	**4,073**	**5,427**	**6,559**	**7,800**	**9,162**	**11,170**
Upper 95%-CI	2,411	4,184	6,116	10,730	17,290	24,700	35,100	55,770
08059000 East Fork Trinity River near McKinney, Tex.								
Lower 95%-CI	3,654	8,034	11,630	15,890	18,090	19,560	20,550	21,380
Estimate	**5,393**	**11,510**	**16,420**	**23,300**	**28,750**	**34,390**	**40,170**	**48,000**
Upper 95%-CI	7,904	16,680	26,700	44,990	62,470	84,860	114,000	167,200
08059400 Sister Grove Creek near Blue Ridge, Tex.								
Lower 95%-CI	1,179	2,398	3,388	4,744	5,750	6,709	7,616	8,735
Estimate	**1,574**	**3,198**	**4,593**	**6,718**	**8,560**	**10,620**	**12,910**	**16,330**
Upper 95%-CI	2,099	4,474	7,151	12,870	19,410	28,600	41,460	66,670
08061540 Rowlett Creek near Sachse, Tex.								
Lower 95%-CI	8,350	15,900	21,560	28,730	33,490	37,580	41,100	45,030
Estimate	**10,700**	**20,220**	**27,680**	**38,140**	**46,560**	**55,440**	**64,770**	**77,810**
Upper 95%-CI	13,680	26,290	38,670	61,210	83,110	110,200	144,000	202,100
08061750 East Fork Trinity River near Forney, Tex.								
Lower 95%-CI	9,885	20,280	27,110	34,960	39,480	42,900	45,470	47,940
Estimate	**13,810**	**26,340**	**34,730**	**44,690**	**51,460**	**57,630**	**63,240**	**69,870**
Upper 95%-CI	18,310	34,080	46,300	65,740	83,430	104,400	130,100	174,500
08062000 East Fork Trinity River near Crandall, Tex.								
Lower 95%-CI	7,680	15,390	21,020	28,360	33,530	38,240	42,460	47,340
Estimate	**9,807**	**19,230**	**26,470**	**36,370**	**44,100**	**52,020**	**60,110**	**71,030**
Upper 95%-CI	12,310	24,420	35,080	54,510	75,680	104,000	142,000	213,100

Table 5.2: Statistically Estimated Annual Flood Flow Frequency Results for Selected U.S Geological Survey Streamflow-Gaging Stations in the Trinity River Basin based on the USGS-PeakFQ EMA-LPIII Computations

Station number and name	Peak-streamflow frequency by corresponding average return period (recurrence interval) in years							
	2 year (ft^3/s)	5 year (ft^3/s)	10 year (ft^3/s)	25 year (ft^3/s)	50 year (ft^3/s)	100 year (ft^3/s)	200 year (ft^3/s)	500 year (ft^3/s)
08062500 Trinity River near Rosser, Tex.								
Lower 95%-CI	21,170	37,230	48,950	63,920	74,470	84,260	93,320	104,300
Estimate	**25,480**	**44,780**	**59,620**	**80,380**	**97,140**	**114,900**	**133,700**	**160,400**
Upper 95%-CI	30,640	55,100	77,740	117,400	156,000	203,200	261,200	358,400
08062700 Trinity River at Trinidad, Tex.								
Lower 95%-CI	27,010	44,320	55,130	68,020	76,580	84,140	90,770	98,320
Estimate	**32,810**	**52,560**	**65,890**	**82,610**	**94,840**	**106,800**	**118,600**	**133,900**
Upper 95%-CI	39,050	63,460	82,440	113,400	144,000	182,500	231,400	317,500
08062800 Cedar Creek near Kemp, Tex.								
Lower 95%-CI	4,101	7,597	10,150	12,960	14,360	15,290	15,910	16,430
Estimate	**5,559**	**10,060**	**13,300**	**17,510**	**20,650**	**23,770**	**26,870**	**30,910**
Upper 95%-CI	7,495	13,460	19,470	29,340	37,980	48,320	60,960	82,310
08063100 Richland Creek near Dawson, Tex.								
Lower 95%-CI	1,432	2,297	2,888	3,630	4,166	4,682	5,179	5,808
Estimate	**1,687**	**2,712**	**3,460**	**4,472**	**5,268**	**6,097**	**6,963**	**8,169**
Upper 95%-CI	1,983	3,296	4,401	6,154	7,766	9,680	11,950	15,610
08063590 Waxahachie Creek at Waxahachie, Tex.								
Lower 95%-CI	642	1,745	2,686	4,026	5,086	6,167	7,250	8,690
Estimate	**1,571**	**3,743**	**5,797**	**9,129**	**12,160**	**15,670**	**19,690**	**25,850**
Upper 95%-CI	3,521	11,680	25,180	62,690	117,700	212,900	377,300	700,800
08063800 Waxahachie Creek near Bardwell, Tex.								
Lower 95%-CI	937	1,438	1,710	2,031	2,255	2,465	2,664	2,912
Estimate	**1,127**	**1,635**	**1,976**	**2,411**	**2,736**	**3,062**	**3,391**	**3,831**
Upper 95%-CI	1,271	1,921	2,425	3,155	3,765	4,433	5,168	6,267
08064100 Chambers Creek near Rice, Tex.								
Lower 95%-CI	8,830	17,630	24,200	32,740	38,970	44,920	50,570	57,560
Estimate	**12,070**	**23,670**	**33,030**	**46,490**	**57,540**	**69,370**	**81,980**	**99,850**
Upper 95%-CI	16,200	33,480	50,450	80,470	110,400	148,000	195,200	275,700
08064700 Tehuacana Creek near Streetman, Tex.								
Lower 95%-CI	5,650	13,550	22,350	37,920	53,230	72,210	95,400	133,600
Estimate	**7,886**	**19,700**	**34,000**	**64,130**	**99,550**	**150,900**	**224,500**	**371,700**
Upper 95%-CI	11,020	32,200	71,000	247,000	677,100	1,583,000	3,718,000	11,570,000
08065000 Trinity River near Oakwood, Tex.								
Lower 95%-CI	26,340	55,980	74,050	94,440	106,700	116,100	123,400	130,500
Estimate	**34,410**	**66,800**	**87,840**	**111,900**	**127,600**	**141,500**	**153,600**	**167,300**
Upper 95%-CI	41,630	79,960	106,100	140,000	166,100	193,700	223,600	268,100

Table 5.2: Statistically Estimated Annual Flood Flow Frequency Results for Selected U.S Geological Survey Streamflow-Gaging Stations in the Trinity River Basin based on the USGS-PeakFQ EMA-LPIII Computations

Station number and name	Peak-streamflow frequency by corresponding average return period (recurrence interval) in years							
	2 year (ft^3/s)	5 year (ft^3/s)	10 year (ft^3/s)	25 year (ft^3/s)	50 year (ft^3/s)	100 year (ft^3/s)	200 year (ft^3/s)	500 year (ft^3/s)
08065200 Upper Keechi Creek near Oakwood, Tex.								
Lower 95%-CI	2,356	6,454	10,320	16,100	20,460	24,550	28,290	32,720
Estimate	**3,404**	**9,168**	**14,780**	**23,890**	**32,070**	**41,350**	**51,750**	**67,190**
Upper 95%-CI	4,880	13,330	23,490	47,030	75,890	118,500	181,200	312,000
08065350 Trinity River near Crockett, Tex.								
Lower 95%-CI	28,160	47,400	59,970	74,170	82,370	88,670	93,540	98,430
Estimate	**34,390**	**56,910**	**71,760**	**89,840**	**102,600**	**114,800**	**126,400**	**141,000**
Upper 95%-CI	41,720	68,480	89,620	123,400	152,500	185,300	223,300	283,400
08065800 Bedias Creek near Madisonville, Tex.								
Lower 95%-CI	6,260	14,200	20,300	28,600	34,600	39,700	43,800	48,200
Estimate	**8,610**	**18,800**	**26,900**	**38,000**	**46,700**	**55,400**	**64,300**	**75,900**
Upper 95%-CI	11,800	24,700	34,900	52,400	70,100	92,000	119,000	163,000
08066000 Trinity River at Riverside, Tex.								
Lower 95%-CI	29,700	50,540	65,010	82,390	93,570	103,100	111,300	120,500
Estimate	**35,340**	**59,790**	**77,410**	**100,700**	**118,600**	**136,800**	**155,300**	**180,400**
Upper 95%-CI	42,010	71,710	97,180	138,100	174,400	216,000	264,100	340,000
08066170 Kickapoo Creek near Onalaska, Tex.								
Lower 95%-CI	4,037	8,547	12,590	18,710	23,940	29,680	35,910	44,870
Estimate	**5,343**	**11,500**	**17,530**	**27,900**	**38,000**	**50,460**	**65,740**	**91,150**
Upper 95%-CI	7,088	16,270	27,170	53,240	89,940	153,500	263,600	541,700
08066200 Long King Creek at Livingston, Tex.								
Lower 95%-CI	5,085	10,330	14,670	20,830	25,690	30,630	35,560	42,040
Estimate	**6,533**	**13,330**	**19,300**	**28,580**	**36,780**	**46,110**	**56,680**	**72,720**
Upper 95%-CI	8,391	17,610	26,970	46,110	68,820	102,000	149,900	246,900
08066250 Trinity River near Goodrich, Tex.								
Lower 95%-CI	40,200	61,700	74,200	88,600	98,100	106,000	113,000	121,000
Estimate	**47,800**	**71,100**	**85,600**	**103,000**	**115,000**	**126,000**	**137,000**	**150,000**
Upper 95%-CI	55,100	81,500	99,200	125,000	148,000	174,000	206,000	256,000
08066300 Menard Creek near Rye, Tex.								
Lower 95%-CI	1,780	3,890	5,720	8,430	10,600	12,900	15,100	17,900
Estimate	**2,360**	**5,110**	**7,550**	**11,400**	**14,700**	**18,500**	**22,800**	**29,100**
Upper 95%-CI	3,060	6,620	10,100	17,300	26,300	40,100	61,100	106,000
08066500 Trinity River at Romayor, Tex.								
Lower 95%-CI	38,210	61,080	74,170	87,680	94,770	99,750	103,300	106,600
Estimate	**44,180**	**69,040**	**83,190**	**98,300**	**107,700**	**115,800**	**122,700**	**130,500**
Upper 95%-CI	50,610	77,530	93,160	112,600	127,200	142,000	157,300	178,700
08067000 Trinity River at Liberty, Tex.								
Lower 95%-CI	31,100	53,400	67,700	85,100	97,100	108,000	118,000	130,000
Estimate	**36,800**	**61,300**	**78,200**	**99,900**	**116,000**	**132,000**	**148,000**	**169,000**
Upper 95%-CI	42,100	71,100	92,900	126,000	158,000	197,000	244,000	322,000

5.3 CHANGES TO FLOOD FLOW FREQUENCY ESTIMATES OVER TIME

Statistically based flow frequency estimates are dependent on observational data and historical information. 18 stream gages were selected for analysis of flow frequency changes over time. The annual recurrence intervals of interest here are 2, 10, 100, and 500 years. The 18 stream gages were selected as those of particular interest of InFRM team members for this type of analysis because they represent locations with especially long record and (or) represent important waypoints in the study of Trinity River basin flood flow hydrology. The stream gage numbers and names are 08042800 (West Fork Trinity River near Jacksboro), 08044500 (West Fork Trinity River near Boyd), 08047500 (Clear Fork Trinity River at Fort Worth), 08048000 (West Fork Trinity River at Fort Worth), 08049500 (West Fork Trinity River at Grand Prairie), 08049700 (Walnut Creek near Mansfield), 08050100 (Mountain Creek at Grand Prairie), 08051500 (Clear Creek near Sanger), 08053500 (Denton Creek near Justin), 08055500 (Elm Fork Trinity River near Carrolton), 08057000 (Trinity River at Dallas), 08057200 (White Rock Creek at Greenville, Avenue, Dallas), 08061540 (Rowlett Creek near Sachse), 08062000 (East Fork Trinity River near Crandall), 08062500 (Trinity River near Rosser), 08065000 (Trinity River near Oakwood), 08066000 (Trinity River at Riverside), and 08066500 (Trinity River at Romayor).

Discussion for each stream gage is not proferred because of considerable similarity or parallelism among the figures. As a result, the earlier listed stream gages have more attendant discussion than later ones. Each of these examples is intended to illustrate that there is a progression in statistical estimates over time as flood events are observed and the sample size available changes. As a note, peaks outside the period of record are not shown.

A progression in the estimates occurs because the total sample size as a measure of information content of flood flows increases at a proportionally smaller rate. For example, one more year of data for a sample of 10 years represents a 10-percent increase information, whereas, one more year of data for a sample of 50 years is only a 2 percent increase in information. In other words, as the record length increases, given other factors remaining relatively constant, the estimates should vary year to year to a lesser degree for the simple reason that proportionally less information is included with each successive year. A striking feature of the figures is the sensitivity of estimates of the 100- and 500-year return period when large floods are observed (included) in the record.

The USGS-PeakFQ software when setup for data processing by EMA does not readily facilitate computations such as those required for similar graphics. The computations involved were based on fitting the LPIII to the L-moments (Asquith, 2011a,b) of the data points shown from a given year backwards in time. The computations included a minimum of 10 years. As a result, the actual starting year varies amongst the figures. The results of USGS-PeakFQ software as listed in Table 5.2 provide the ordinates for 2016 (right-most side of curves ending between 2010 and 2020 in the figures), and logarithmic-derived offsets between the L-moment-based LPIII fit in 2016 were used to adjust the curves in prior years for each of the four recurrence intervals.

The estimates are necessarily sensitive to the coefficient of skewness computed. For example, a postitive value for skewness and the LPIII distribution can lead to rapidly increasing flood flow estimates. The 500-year return period streamflow can be much larger than the 100-year return period. Conversely, a negative value of skewness can lead to only a modest increase in streamflow between the 100-year and 500-year return period. The LPIII shows a finite upper bound. Skewness can abruptly change magnitude and even its sign (negative or positive) when large flood events become included in the record. 3 gages were included in this chapter as examples of how flow frequency can change over time. The complete list of flow frequency change over time results can be found Appendix A – Statistical Hydrology.

West Fork Trinity River at Grand Prairie, Texas

Relative impact of record length and magnitudes of substantial floods for West Fork Trinity River at Grand Prairie are shown in Figure 5.7. The estimates show tendencies that will be shown in many of the other figures. First, the estimates tend to stabilize in time as the record length increases. Second, the 2-year return period does not vary much and this is because this estimate is largely the median annual peak, and in succession, as return period increases the variation in the estimates increase. Third, there often is an asymmetrical saw tooth pattern to the curves. Focusing on the 100-year estimates, it is seen that the estimates tend to jump when large floods occur in the record and then gradual decline as more typical flood events occur. There are two notable upswings in the estimates in about 1960 and again in about 1990, which show the impacts of the top five events in the observational record.

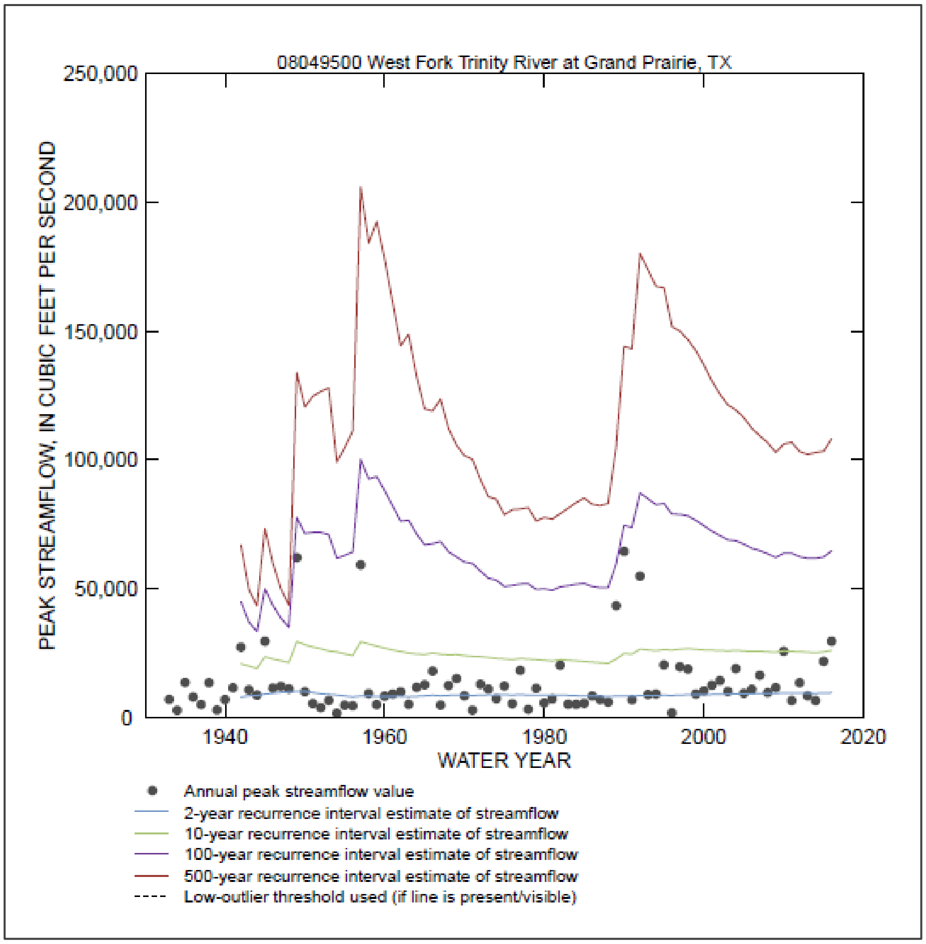


Figure 5.7: Statistical Frequency Flow Estimates Versus Time for 08049500 West Fork Trinity River at Grand Praire

Trinity River at Dallas, Texas

Relative impact of record length and magnitudes of substantial floods for Trinity River at Dallas are shown in Figure 5.8. Similar discussion as for Figure 5.7 is applicable. Perhaps the most striking feature of the estimates are a generalized decline for the data shown with only a modest increase with the cluster of three large events in about 1990.

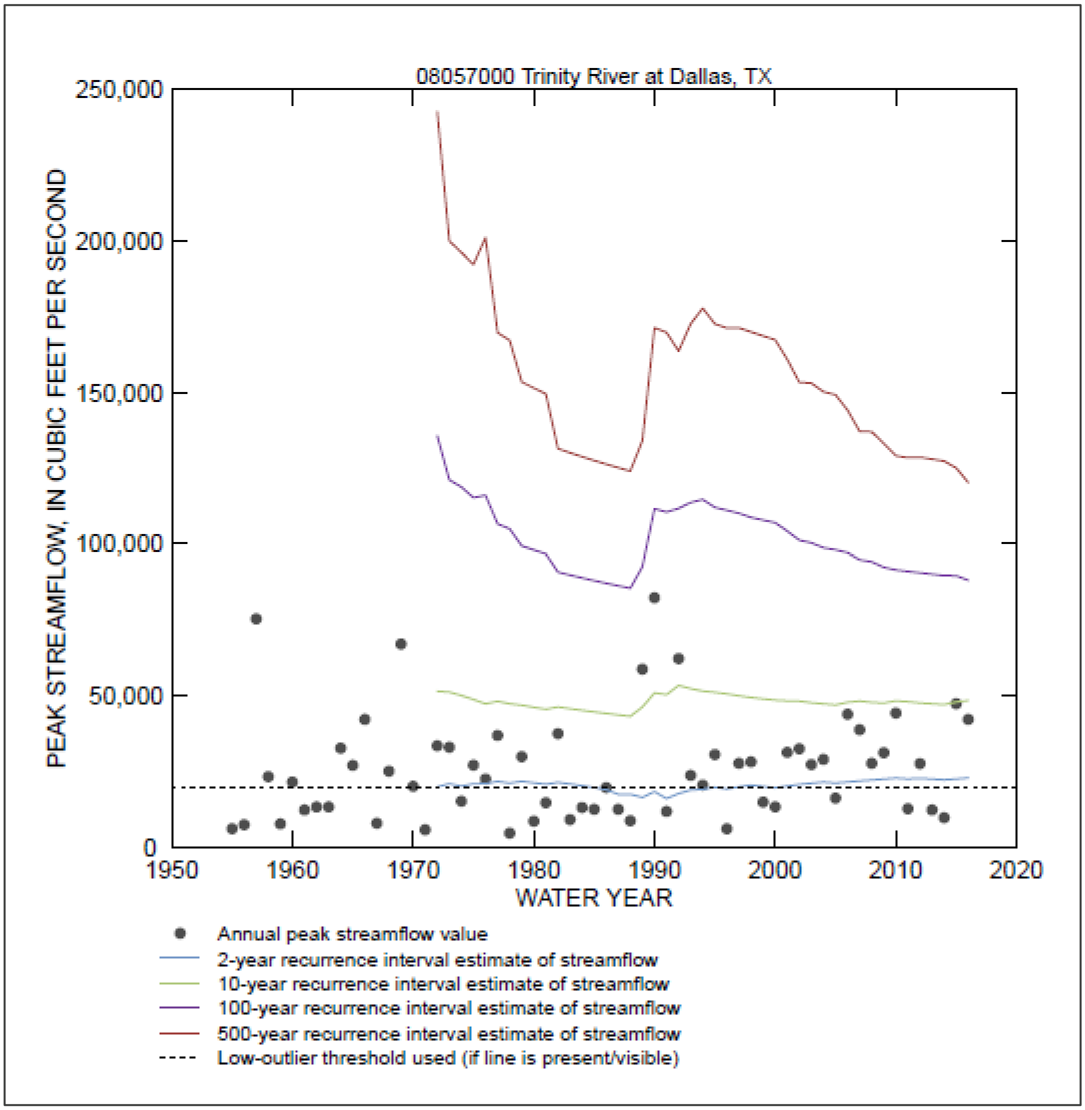


Figure 5.8: Statistical Frequency Flow Estimates Versus Time for 08057000 Trinity River at Dallas

Trinity River near Rosser, Texas

Relative impact of record length and magnitudes of substantial floods for Trinity River near Rosser are shown in Figure 5.9. Similar discussion as for Figure 5.7 is applicable. It is notable that there appears to be a persistent generalized decline in estimates throughout the period of data even in the context of two large events at the end of the record in 2015 and 2016.

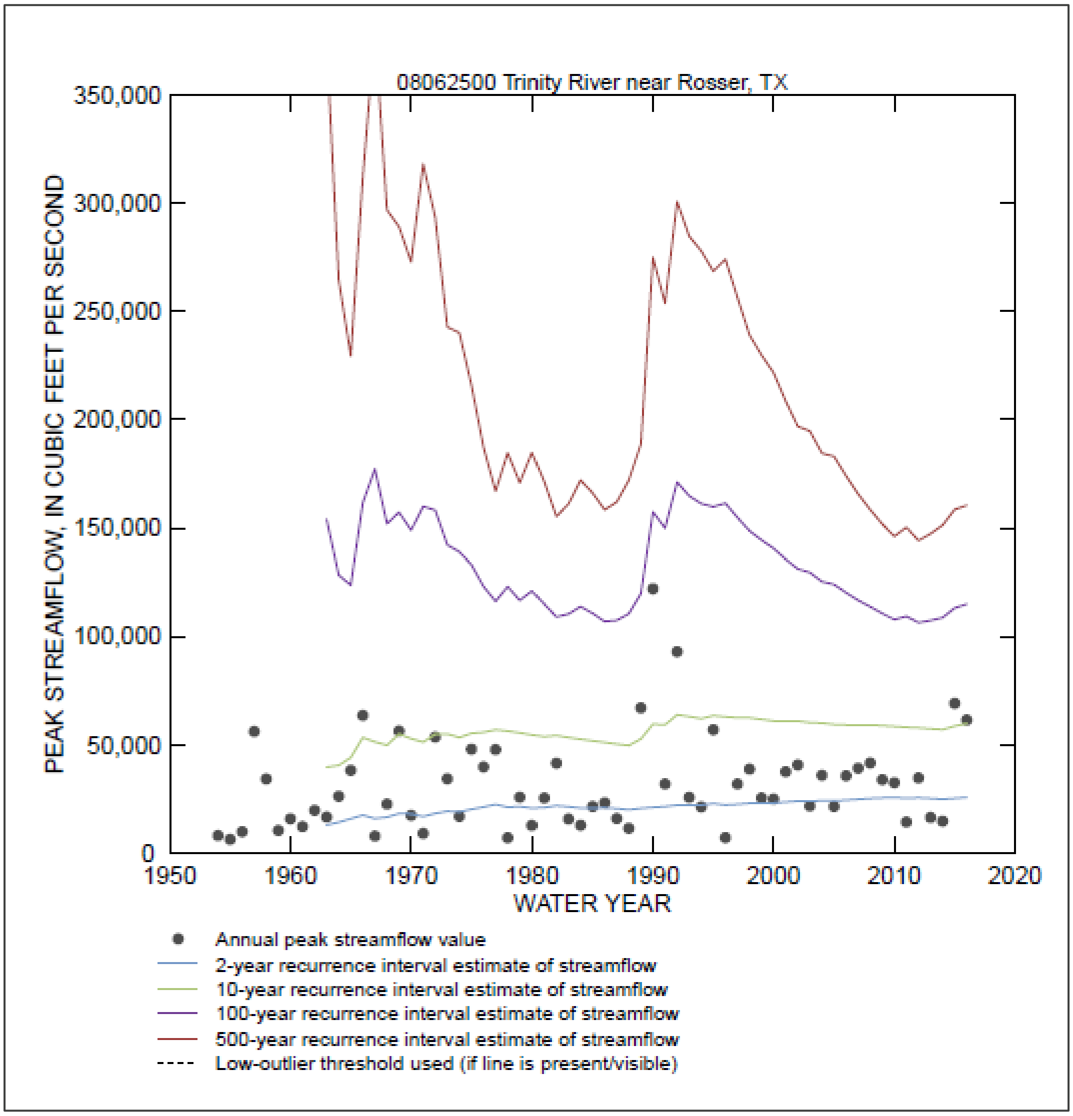


Figure 5.9: Satistical Frequency Flow Estimates Versus Time for 08062500 Trinity River near Rosser

5.4 INFLUENCE OF CLIMATIC VARIABILITY

Stochastically, annual peak streamflow does not occur at the same time in each water year. Each year the annual peak streamflow for a stream gage is generated by the watershed from immensely complex interactions. These interactions include weather patterns and discrete rainfall events and physical aspects of the terrain coupled with the amalgamation of the arrival times of flood waves amongst tributaries. Arrivial times are simultaneously dependent on conditional storage conditions, infiltration capacity conditions, antecedent moisture, and also the pre-existing fullness of channels when the peak-producing rains occur. Storage conditions represent both manmade structures (reservoirs and detention basins) but also nonpoint storage such as initial watershed losses and depression storage. Conversely, some water years might effectively have such limited rainfall input that residual waters draining for many months or longer periods of previous rainfall episodes would not be considered as "flood events." The conditional status of the watershed is influenced by general climate conditions because such conditions express antecedent moisture conditions.

A sensitivity study was conducted to evaluate the effects of climate variability on the record. Runoff and soil loss rates in Texas have been observed to vary greatly from one storm to another, depending on the antecedent moisture conditions of the soil at the time of the storm. Therefore, for this sensitivity test, the Palmer Drought Severity Index (PDSI) was used at the time of each recorded annual peak to divide the streamflow-gaging stations record into a "wet" peak series and a "dry" peak series. For each of the 55 stream gages of this greater study, a threshold of PDSI demarking dry and wet conditions for the month of each annual peak streamflow was selected as PDSI = 1.6, which approximately bifurcates the data. An annual peak occurring in a month having PDSI less than or equal to 1.6 was classified as a dry condition peak and conversely an annual peak occurring in a month having PDSI greater than 1.6 was classified as a wet condition peak. In particular, the PDSI is used to distinguish between periods of below typical and abundant moisture conditions. Details about the PDSI are described by Palmer (1965) and other information is available from the National Centers for Environmental Information ([NCEI], 2017a,b,c,d).

The PDSI threshold of 1.6, though for all of the 55 gages, was logically held for just18 stream gages.. These are the same stream gages used in the previous section for purposes of parallelism. It is necessary to clarify a subtle point when interpreting the below figures. The exceedance probability (recurrence interval) axis (horizontal) can be considered correct in regards to the entire sample. This axis is correct for the smaller samples if one imagines a scenario where all peaks, although now about half the original sample, were for wet conditions and vice versa for the dry conditions. Though the samples are about equal sizes, it is technically complicated to remix the frequency curves for wet and dry conditions into the same probability scale as all the data. Thus, the primary purpose of these figures is to show how substantial or not the coupling between PDSI (the index of climate conditions) and annual peak streamflow in the study might be. While only 2 gages are included in this chapter, the complete list of results can be found in Appendix A – Statistical Hydrology.

West Fork Trinity River at Fort Worth, Texas

West Fork Trinity River at Fort Worth was selected as one example. Annual peak streamflow data split between wet and dry conditions are shown in Figure 5.10. The LPIIII distribution was fit to each type of peak streamflow using L-moments. The low-outlier threshold as reported in Table 5.1 was used and was held constant for each wet condition (blue circles) or dry condition (red circles) sample. Several interpretations of the results shown can be made, which are also generally applicable to the other 17 figures. First, on average, wet condition peaks are larger than dry condition peaks and as a typical rule these peaks plot above or further up the vertical axis than the dry condition peaks. This is the case for this stream gage. Second, if wet condition peaks are larger than dry condition peaks then, in general, for the whole sample (open circles) the blue open circles will tend to plot towards the right. Third, often the dry condition peaks represent the smallest values in the sample and conversely the wet condition peaks represent the largest values. It is important to consider that the PDSI is an index associated for an entire month and the peak occurs on a discrete day of the month. Also consider that a peak occurring on the first of a month might be more associated to the prior month. Alternatively, consider that the PDSI is representative of a large region and not precisely the watershed, which might receive locally intense rainfall responsible for the large peak. This is a long record site. The curves appear to become parallel towards the right. The largest peak in the record is classified as a dry condition peak and, in relation to the other dry peaks, is clearly an outlier.

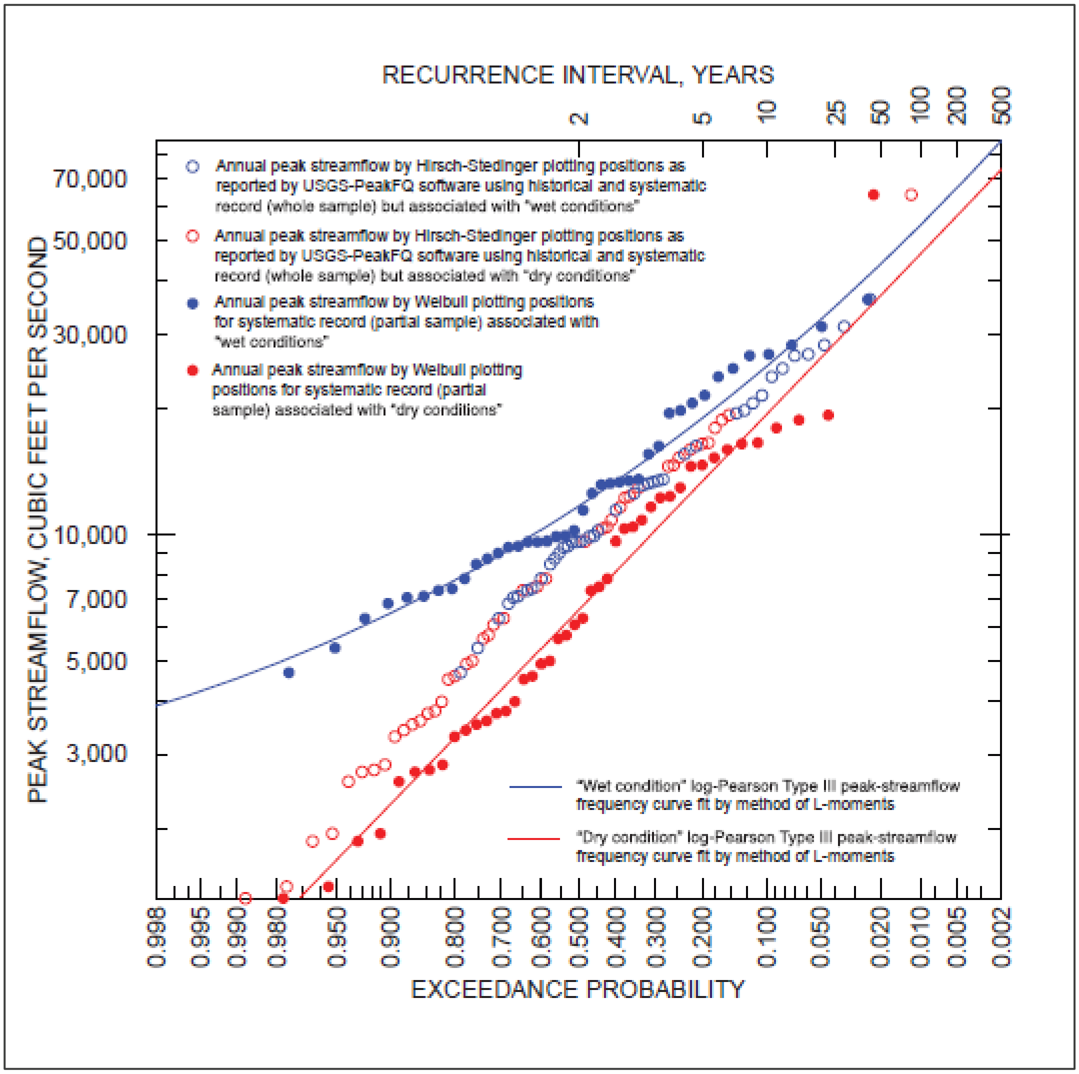


Figure 5.10: Effects of Climate Variability as Expressed by a Threshold of the Palmer Drought Severity Index of 1.6 on the Flow Frequency Curve for 08048000 West Fork Trinity River at Fort Worth

Trinity River at Dallas, Texas

Trinity River at Dallas was selected as one example. Annual peak streamflow data split between wet and dry conditions are shown in Figure 5.11. Similar discussion as for Figure 5.10 is applicable. The curves intersect each other for a comparatively small recurrence interval. This is caused by the steeper right tail of the dry condition peaks relative to the wet condition peaks.

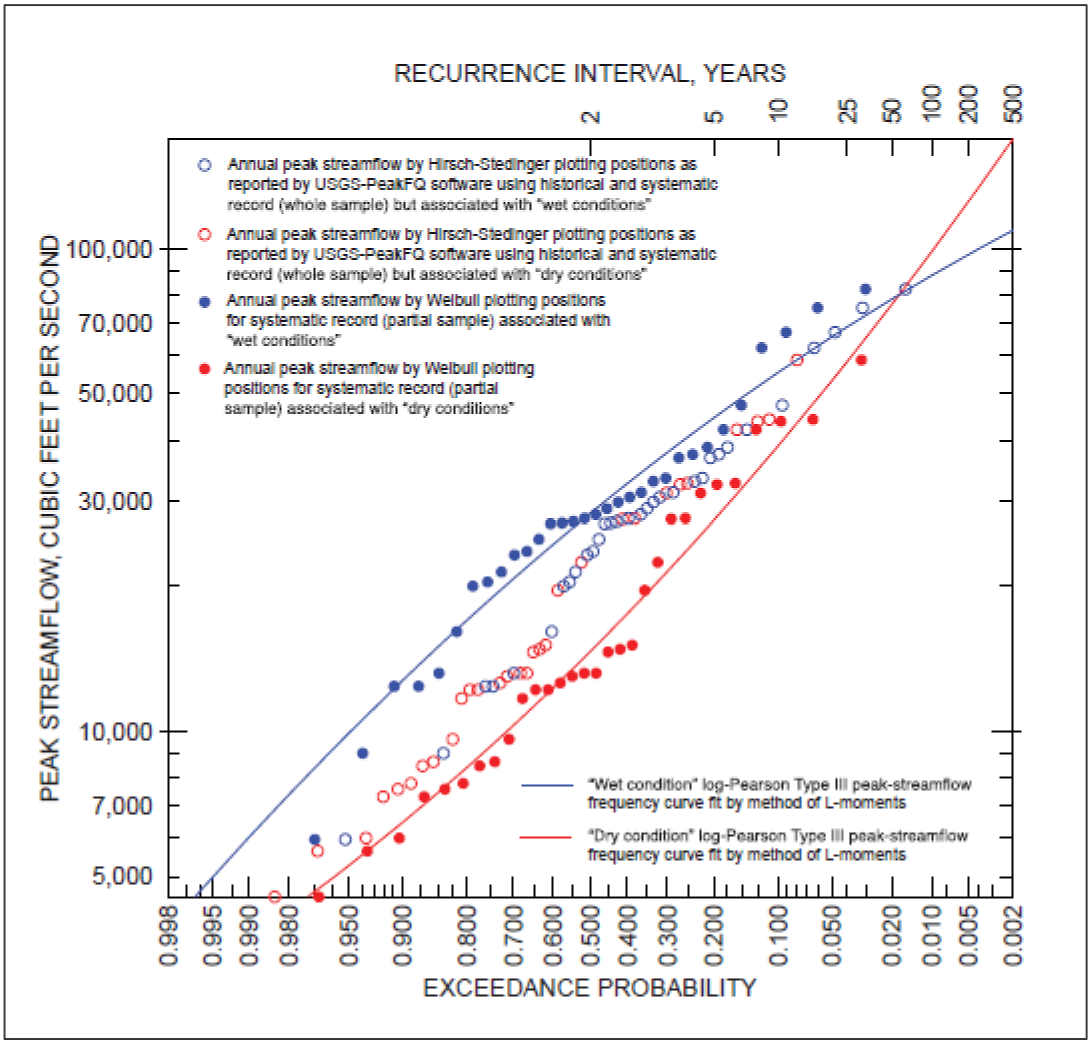


Figure 5.11: Effects of Climate Variability as Expressed by a Threshold of the Palmer Drought Severity Index of 1.6 on the Flow Frequency Curve for 08057000 Trinity River at Dalls

6 Rainfall-Runoff Modeling in HEC-HMS

Watershed rainfall-runoff modeling is often used to estimate the rare frequency events whose return periods exceed the gaged period of record as well as to account for non-stationary watershed conditions such as urban development, reservoir storage and regulation, and climate variability. Rainfall-runoff modeling also provides a means of estimating flood frequency flows at other locations throughout the watershed that do not coincide with a stream flow gage. Rainfall-runoff watershed modeling is used to simulate the physical processes that occur during storm events that move water across the land surface and through the streams and rivers.

In this phase of the multi-layered hydrologic analysis, a watershed model was built for the Trinity River Basin with input parameters that represented the physical characteristics of the watershed. The rainfall-runoff model for the basin was completed using the basin-wide Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) model developed for the 2015 Trinity Basin Corps Water Management System (CWMS) implementation as a starting point. This model was further refined by adding additional detailed data, updating the land use, and calibrating the model to multiple recent flood events. Through calibration, the updated HEC-HMS model was verified to accurately reproduce the response of the watershed to multiple, recently observed storm events, including those similar in magnitude to a 1% annual chance (100-yr) storm. Finally, frequency storms were built using the depth area analysis in HEC-HMS and the latest published frequency rainfall depths from National Oceanic and Atmospheric Administriation (NOAA) Atlas 14 (NOAA, 2018). These frequency storms were run through the verified model, yielding consistent estimates of the 1% annual chance (100-yr) and other frequency peak flows at various locations throughout the basin.

6.1 HEC-HMS MODEL FROM THE TRINITY CWMS IMPLEMENTATION

The HEC-HMS model from the Trinity CWMS Implementation was used as the starting point for the current study. The CWMS model contained 289 subbasins in the Trinity River Basin and totaled approximately 17,889 square miles. The model extended from the headwaters to Trinity Bay. The subbasins were delineated using the HEC-GeoHMS program and utilized 30-meter National Elevation Dataset (NED) terrain data. The Trinity CWMS HEC-HMS model used the following methods.

- **Losses** – Initial and Constant
- **Transform** – Snyder Unit Hydrograph
- **Baseflow** – Recession
- **Routing** – Lag, Modified Puls, Muskingum, and Straddle Stagger
- **Computation Interval** – 60 minutes

A map of the Trinity CWMS subbasins are shown in Figure 6.1. More information on the CWMS model development is given in the final CWMS report for the Trinity River Basin (USACE, 2015).

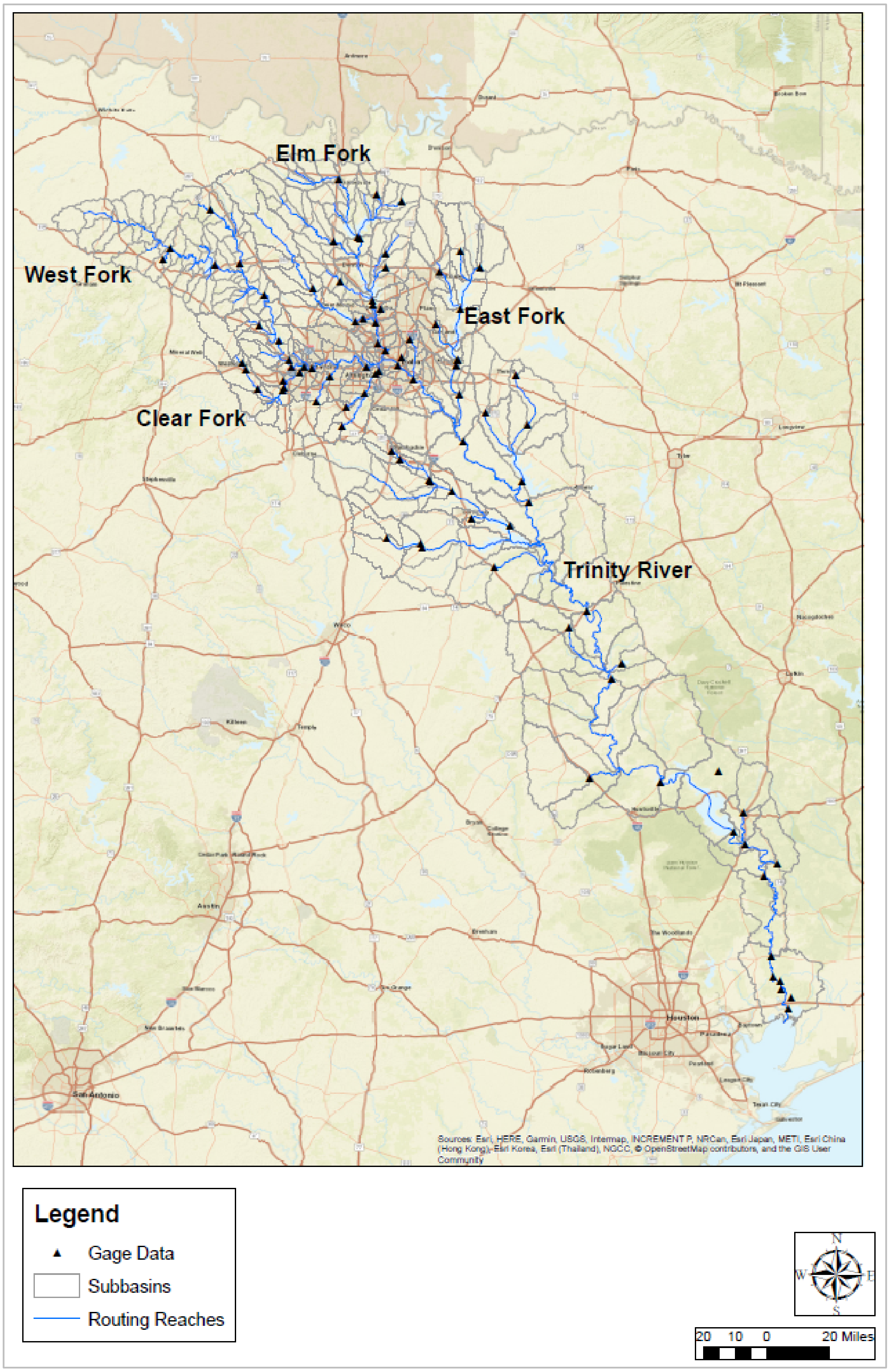


Figure 6.1: CWMS Subbasins for the Trinity River Basin

6.2 UPDATES TO THE HEC-HMS MODEL

The subbasin layout was reviewed and determined sufficient for the study. One of the important components of this study is to utilize information at U.S. Geological Survey (USGS) gages for model calibration and results comparison. Inclusion of the gage locations in the model was a priority during the CWMS modeling and so additional subdivision was not required.

During the study, Federal Emergency Management Agency (FEMA) Base Level Engineering (BLE) hydraulic HEC-RAS models became available and were utilized to improve the hydraulic routing data within the Richland-Chambers watershed where detailed hydraulic modeling was available. These models were built off of detailed topographic data as opposed to the 10m NED digital elevation model (DEM) data used in the 2015 CWMS model used to develop routing data below Bardwell and Navarro Mills dams. This hydraulic routing data includes storage-discharge tables which are extracted from the hydraulic models and are used for the Modified-Puls routing method which calculates the change in flow through the reach based on the volume of floodplain storage through that reach.

Finally, after updating the above data within the Richland-Chambers watershed, the computation interval of the model was also increased from 60 to 15 minutes.

6.3 HEC-HMS MODEL INITIAL PARAMETERS

The InFRM Trinity River HEC-HMS model methods includes initial and constant losses, Snyder unit hydrograph transform parameters, recession baseflows, and Modified Puls, Muskingum, Straddle Stagger, and Lag routing. The sources of the initial estimates for these parameters are described below. All of the model parameters, excluding the percent impervious values, were adjusted during model calibration.

- Initial Loss and Constant Loss Rate –.Initial estimates of losses were made using NRCS soil data. The constant loss rate estimates in the model ranged from 0.03 to 0.26 depending on soil type. These losses were adjusted during calibration and varied significantly between events. The initial estimates for the constant loss rates for the calibration runs were based on National Resources Conservation Service (NRCS) soil type. These differ slightly from the Fort Worth District Loss Rates methodology in that the Fort Worth District Loss Rates vary by frequency. The constant losses were very different for each calibration event based on the soil moisture condition. The initial loss rate estimates as well as the final frequency loss rates fell within the range of the events observed during calibration.
- Percent Impervious – The percent impervious values were developed based on the 2011 National Landcover Database (NLCD) percent developed impervious dataset. The 2011 data was available upon study initiation but was superceded with 2016 data before study completion.
- Snyder Transform Parameters – Initial estimates of transform parameters utilized existing models as much as possible. The methods used to develop parameter estimates as well as the level of calibration applied to each model varied. A table of the existing models utilized to develop initial parameter estimates is shown below.

Table 6.1: Existing Models Utilized to Develop Initial Parameter Estimates

Location	Initial Method/Model Type	Agency	Year	Calibrated
West Fork upstream of Lake Worth Dam	Regional Ct/Forecast Model (HEC-1)	TRWD	2013	Yes
Clear Fork upstream of Benbrook Dam	Urban Curves/Upper Trinity Feasibility Model(HEC-1)	USACE	1995	Yes
Area between Lake Worth Dam, Benbrook Dam, and Lewisville Dam downstream to Trinity at Five Mile Creek	Urban Curves/CDC Model (Model parameters recomputed using existing condition (2005) land use)	USACE	2013	No
Elm Fork Trinity upstream of Lewisville Dam	Urban Curves/Lewisville Dam Safety Mod. Study	USACE	2010	Yes
East Fork Trinity upstream of Crandall Gage	Regional Ct/Forecast Model (HEC-1)	USACE	1996	Yes
Area between Trinity nr Rosser Gage downstream to confluence with Chambers Creek.	Regional Ct/Lower Trinity Reconaissance Study (HEC-1)	USACE	1991	No

Where existing models were not available, engineering judgement was utilized in assigning initial parameter estimates.

Of the existing models, the majority of the models utilized the U.S. Army Corps of Engineers (USACE) Fort Worth District urban curves to develop initial parameter estimates. These curves recommend time to peak and peaking coefficients and are based on length and slope watershed characteristics extracted from HEC-GeoHMS, percent urban values taken from land cover data, and percent sand values estimated from the NRCS soil data. From this data, the following regional equation, which was developed as part of the Fort Worth District urban studies (Nelson, 1979) (Rodman, 1977) (USACE, 1989), was used to calculate lag time:

*log (tp) = .383log (L*Lca/(Sst ^ .5))+(Sand*(log1.81-log.92)+log.92)-(BW*Urban./100)*

where: tp = Snyder's lag time (hours)

L = longest flow path within the subbasin (miles)

Lca = distance along the stream from the subbasin centroid to outlet (miles)

Sst = stream slope over reach between 10% and 85% of L (feet per mile)

Sand = percentage of sand factor as related to the permeability of the soils

(0% Sand = low permeability, 100% Sand = high permeability)

BW = log(tp) bandwidth between 0% and 100% urbanization = 0.266 (log hours)

Urban. = percentage urbanization factor

The remaining rainfall-runoff models utilized regional Ct and peaking coefficient values which were developed regionally.

- **Baseflow Parameters** – Initial baseflow parameters were taken from the existing USACE Trinity CWMS HEC-HMS model, which utilized values from existing models. The existing models that were used are identified in Table 6.1 above.
- **Routing Parameters** (Modified Puls, Muskingum, Straddle Stagger, and Lag) – Routing parameters were taken from the existing USACE Trinity CWMS HEC-HMS model, which utilized values from existing models that are listed in Table 6.1 above.

The complete list of initial parameter tables are included in Appendix B – Rainfall Runoff Modeling in HEC-HMS.

6.4 HEC-HMS MODEL CALIBRATION

After building the HEC-HMS model with its initial parameters, the InFRM team calibrated the model to verify it was accurately simulating the response of the watershed to a range of observed flood events, including large events similar to a 1% annual chance (100-yr) flood. A total of 17 recent storm events were used throughout different parts of the watershed to fine tune the model, as shown in Table 6.2. The model calibration and verification process undertaken during this study exceeds the standards of a typical FEMA floodplain study.

For these storms, the National Weather Service (NWS) hourly rainfall radar data allowed the team to fine tune the watershed model through detailed calibration. Prior to the late 1990s, the NWS radar data was not available for use during earlier modeling efforts. The final model results accurately simulate the observed response of the watershed, as it generally reproduced the timing, shape, and magnitudes of the observed floods. Table 6.2 lists the storms that were used to calibrate each portion of the watershed, and Figure 6.2 through Figure 6.18 illustrate the total depth of rain for the major calibration storms and how that rain was distributed spatially throughout the Trinity River watershed. These plots were extracted from the HEC-MetVue meteorological program for visualizing and processing rainfall data.

Since the rain fell on different parts of the basin from one event to another, the calibration of each storm was focused on those areas of the basin that received the greatest and most intense rainfall. Calibration was also only performed when the USGS stream gages were recording for that event. Table 6.3 shows which storms were calibrated for each USGS stream gage.

Table 6.2: Storm Events Used for Model Calibration

Storm Event	West Fork above Grand Praire Gage	Elm Fork to Trinity Below Dallas Gage	Above Richland-Chambers Reservoir	Trinity below Dallas Gage and below Richland-Chambers Reservoir
Dec-91		Yes		
Apr-99				Yes
Jun-00	Yes			
Jun-04	Yes			
Nov-04				Yes
Oct-06				Yes

Storm Event	West Fork above Grand Praire Gage	Elm Fork to Trinity Below Dallas Gage	Above Richland-Chambers Reservoir	Trinity below Dallas Gage and below Richland-Chambers Reservoir
Mar-07	Yes			
Jun-07		Yes		Yes
Jul-07				Yes
Sep-09			Yes	
Oct-09			Yes	
Sep-10		Yes		Yes
May-15	Yes		Yes	Yes
Jun-15	Yes			
Oct-15			Yes	
Nov-15	Yes	Yes		Yes
Dec-15				Yes

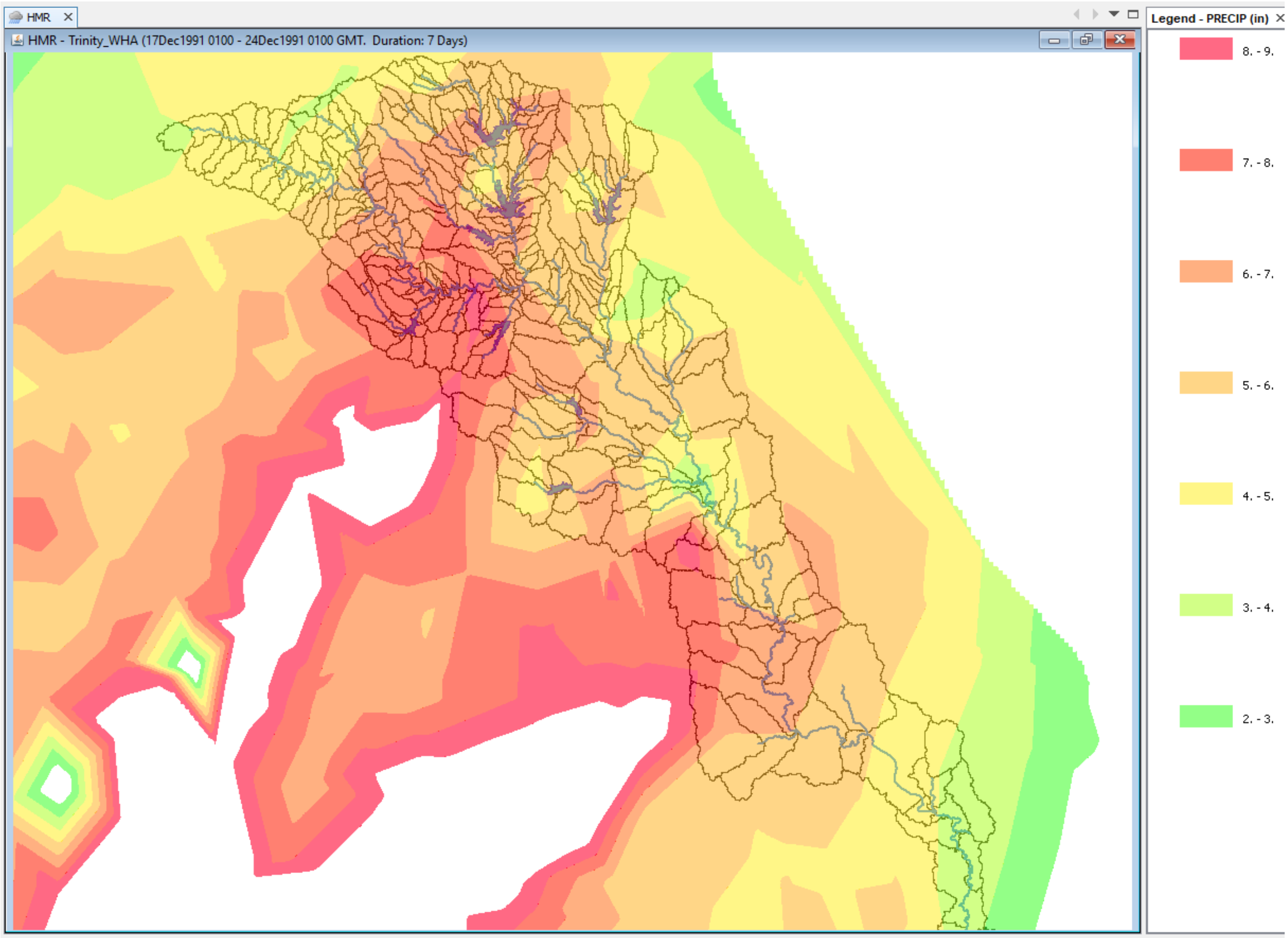


Figure 6.2: Rainfall Depths (inches) for the December 1991 Calibration Storm

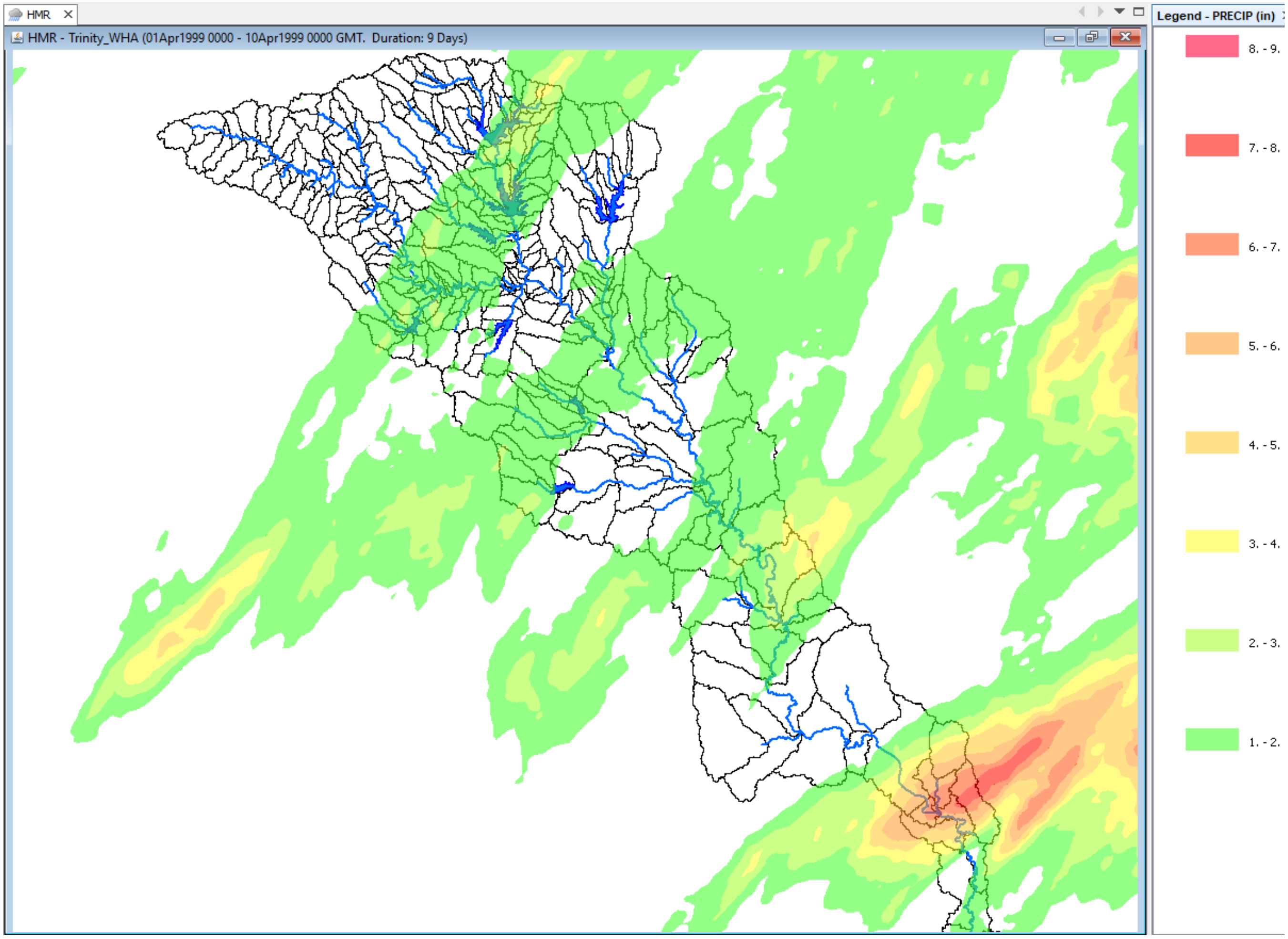


Figure 6.3: Rainfall Depths (inches) for the April 1999 Calibration Storm

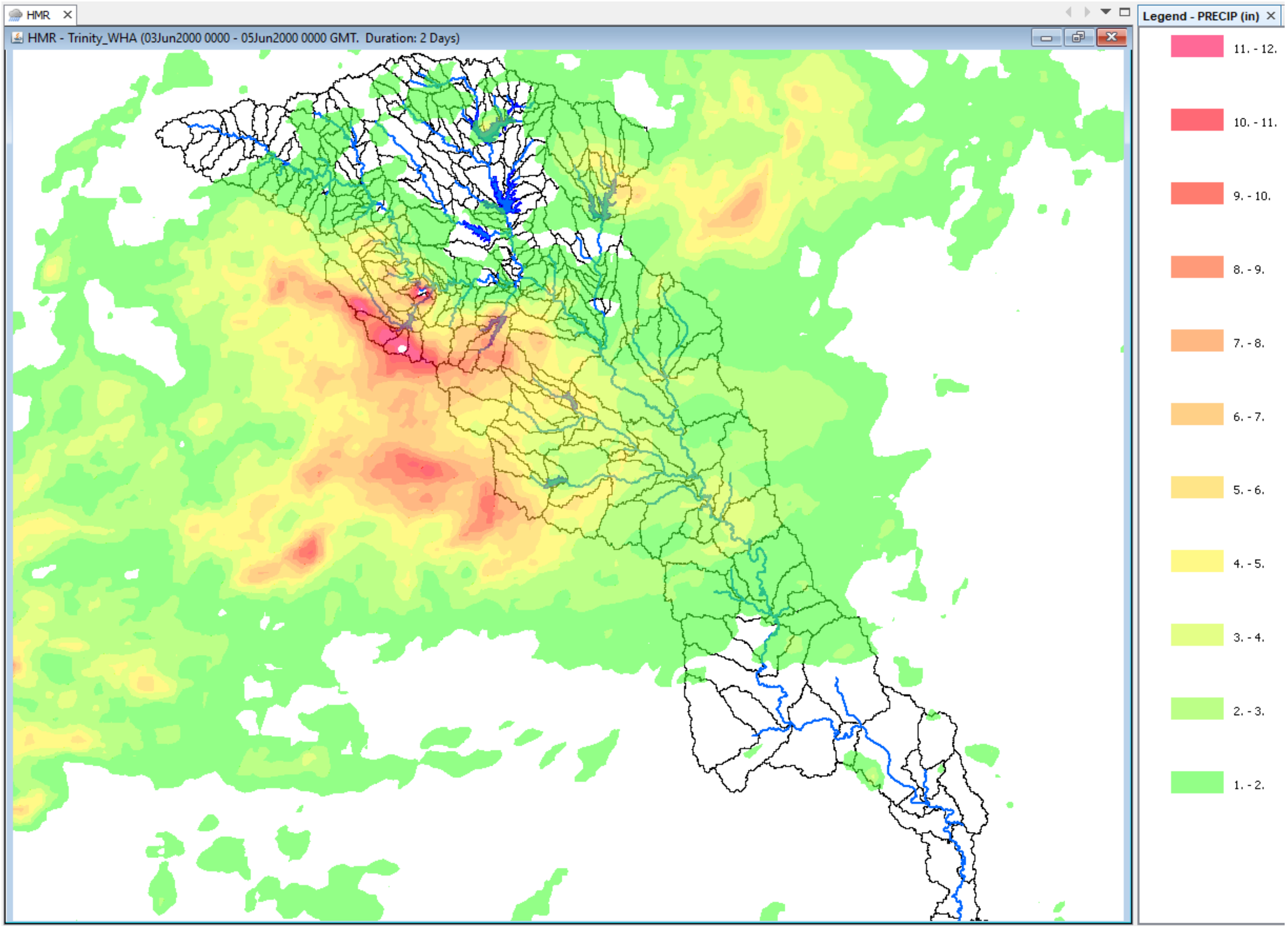


Figure 6.4: Rainfall Depths (inches) for the June 2000 Calibration Storm

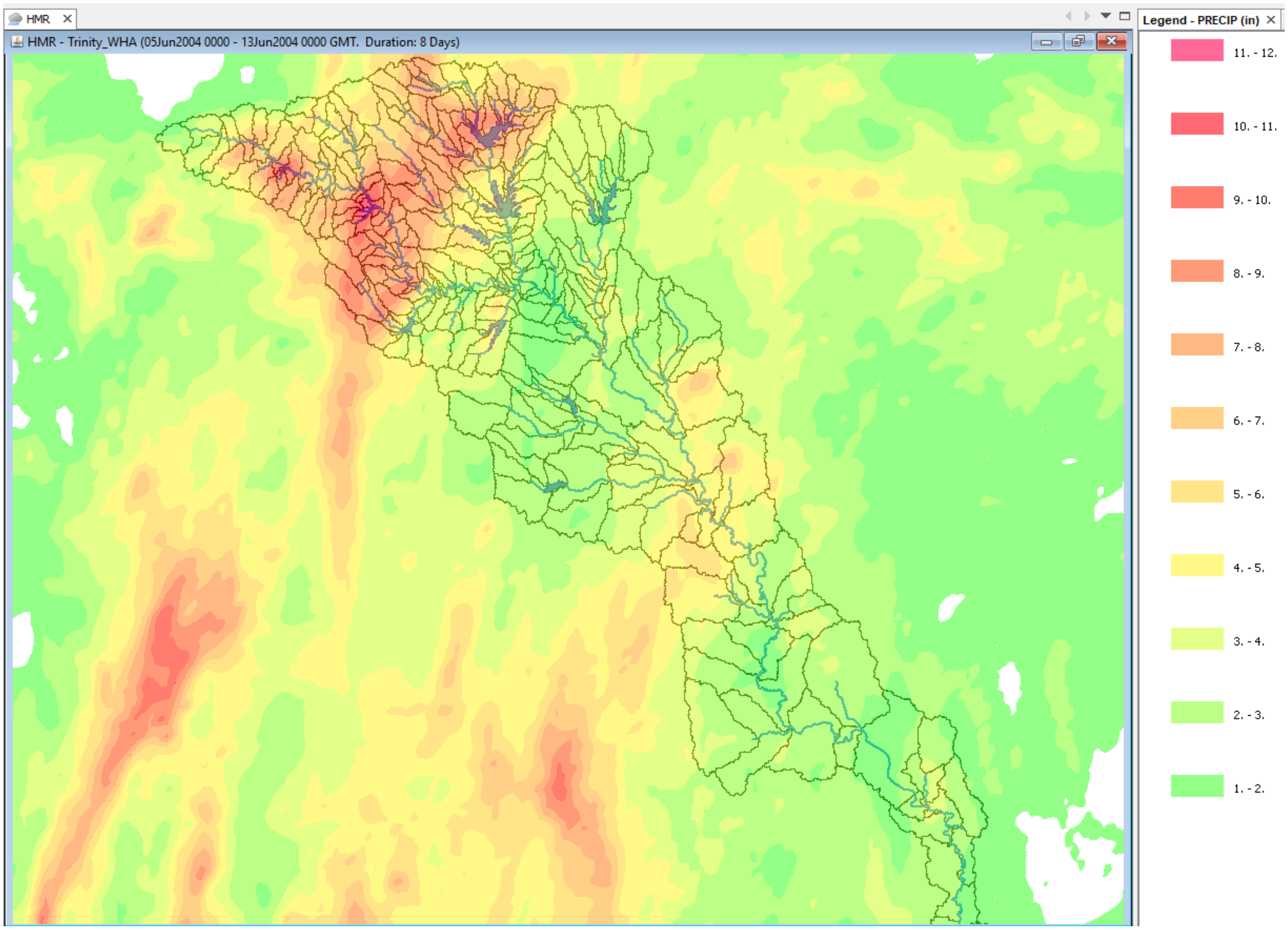


Figure 6.5: Rainfall Depths (inches) for the June 2004 Calibration Storm

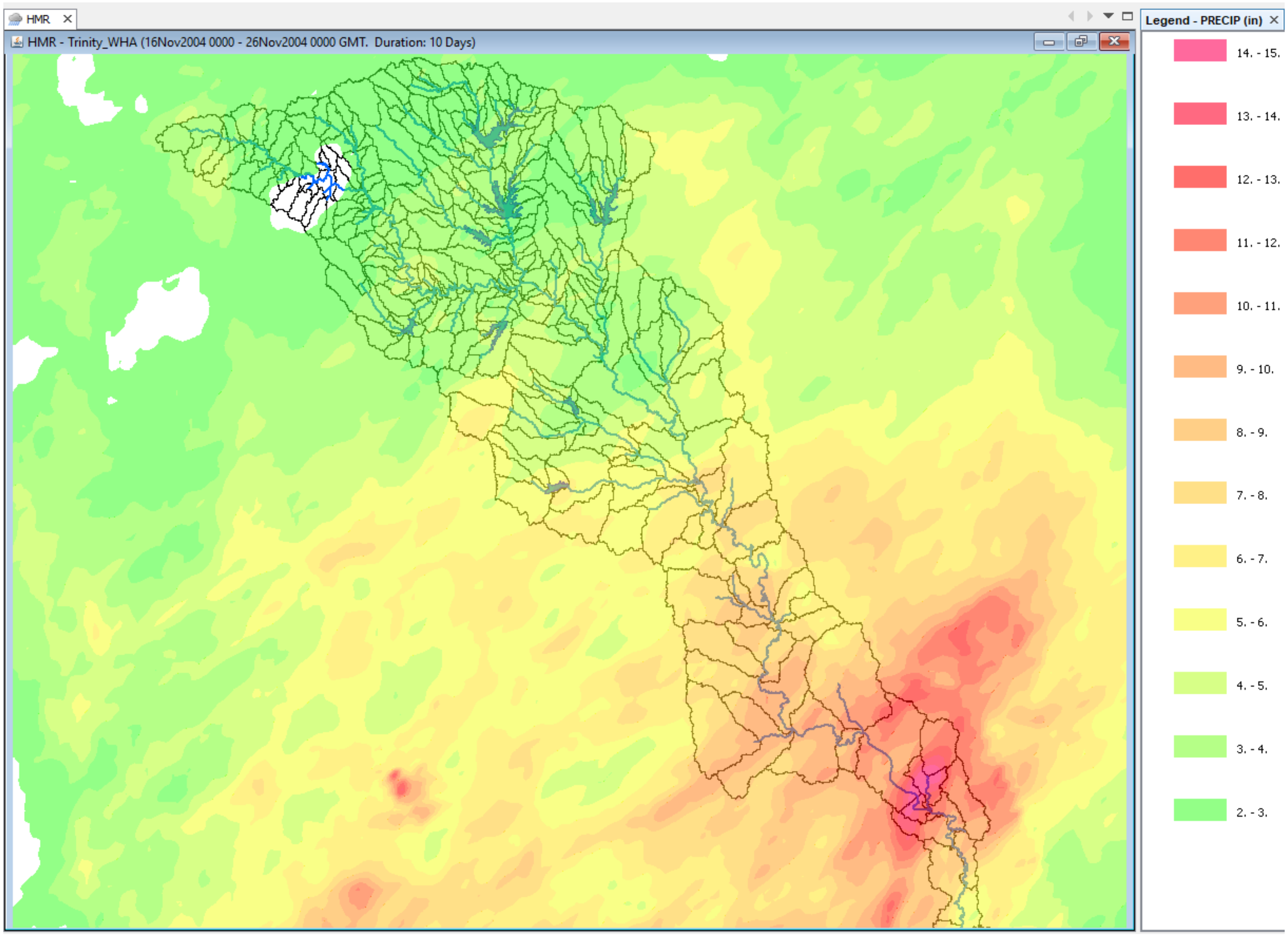


Figure 6.6: Rainfall Depths (inches) for the November 2004 Calibration Storm

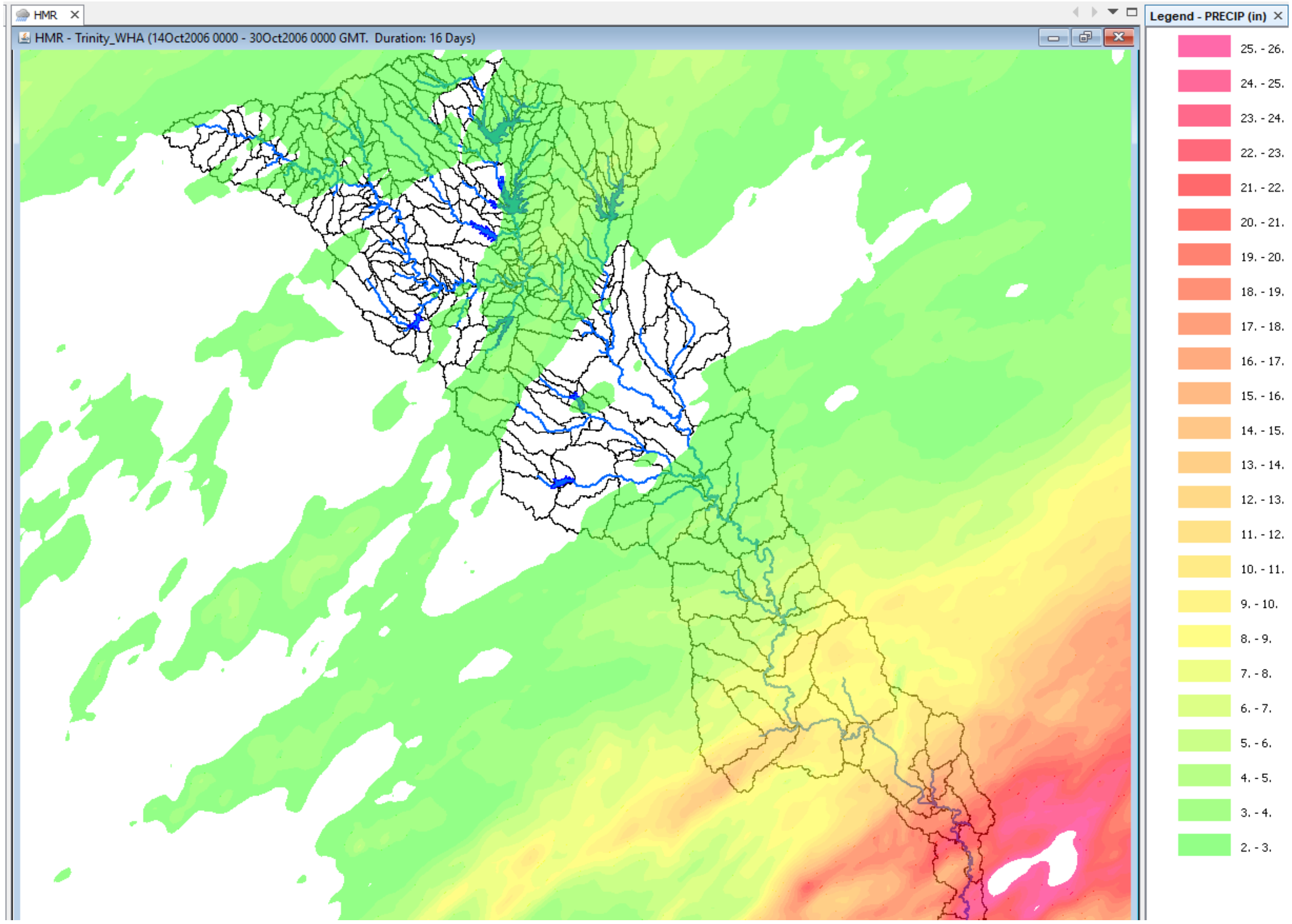


Figure 6.7: Rainfall Depths (inches) for the October 2006 Calibration Storm

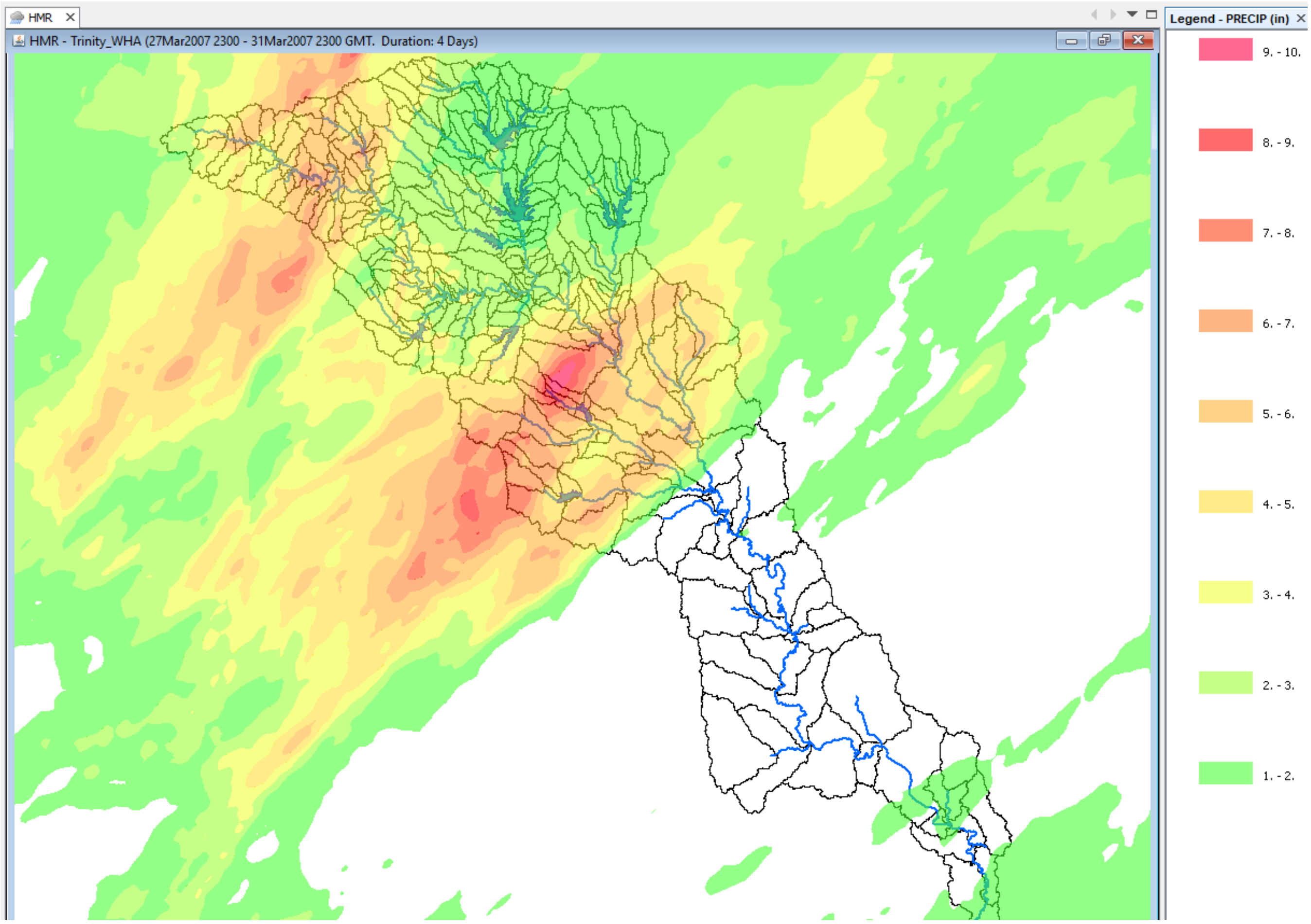


Figure 6.8: Rainfall Depths (inches) for the March 2007 Calibration Storm

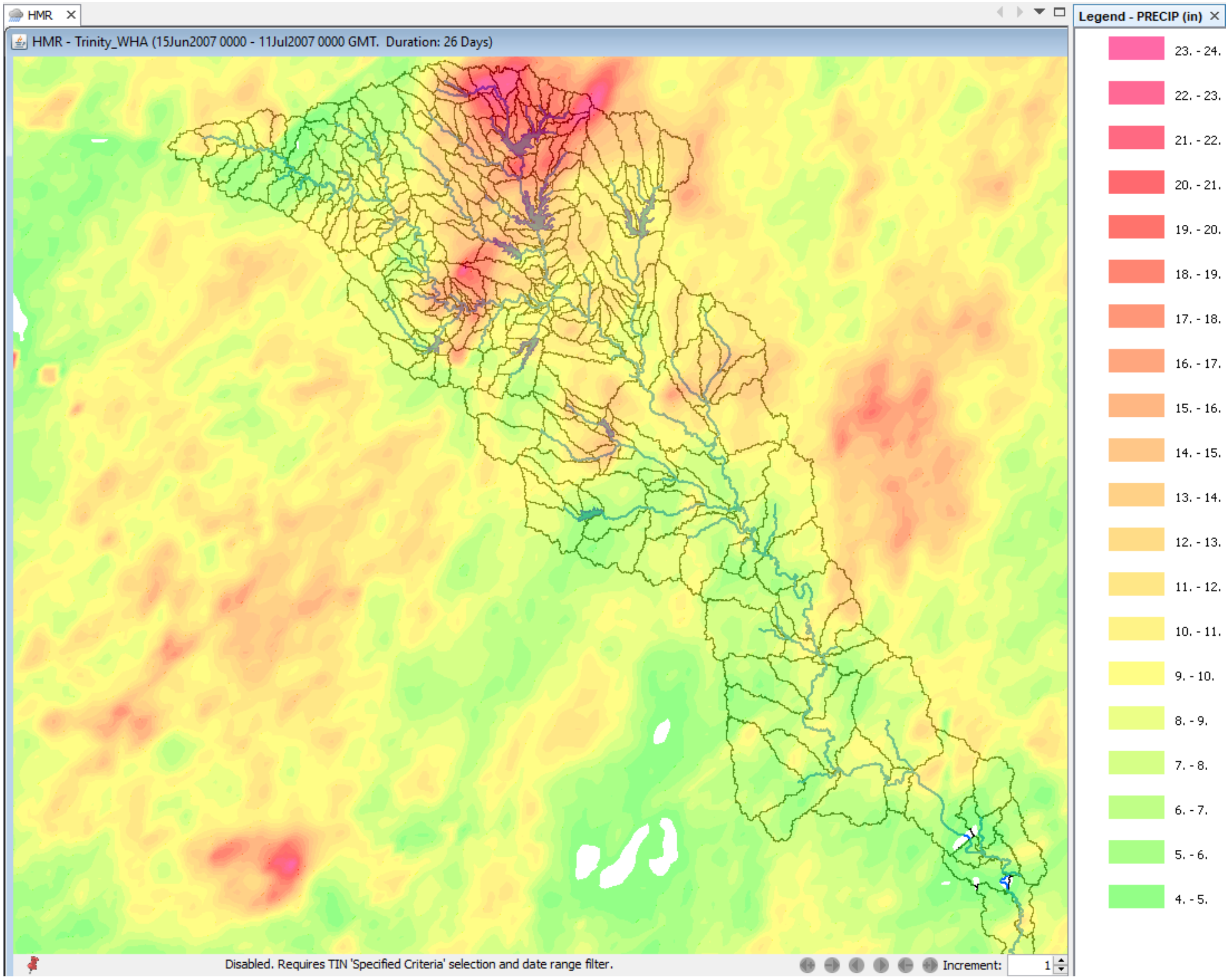


Figure 6.9: Rainfall Depths (inches) for the June 2007 Calibration Storm

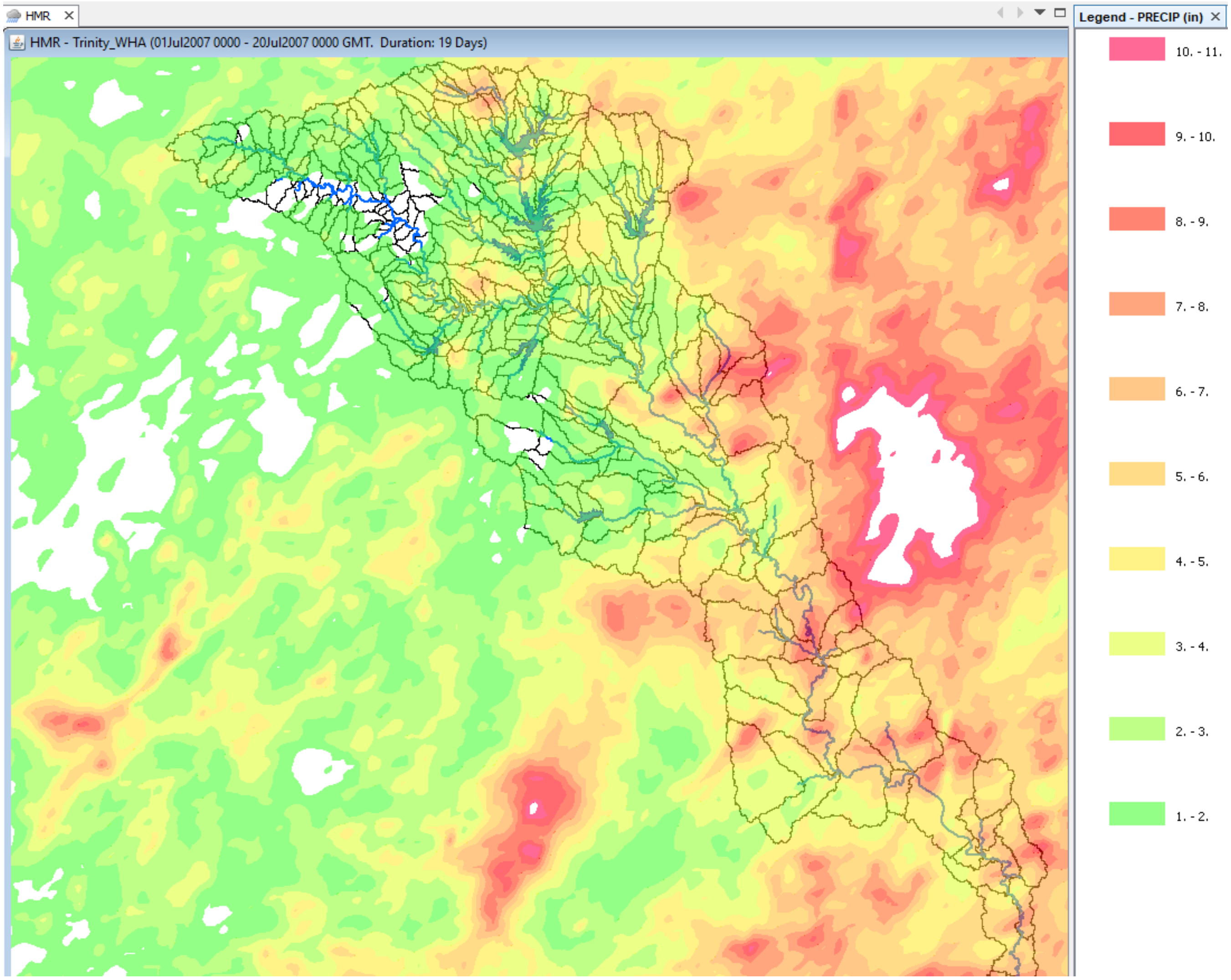


Figure 6.10: Rainfall Depths (inches) for the July 2007 Calibration Storm

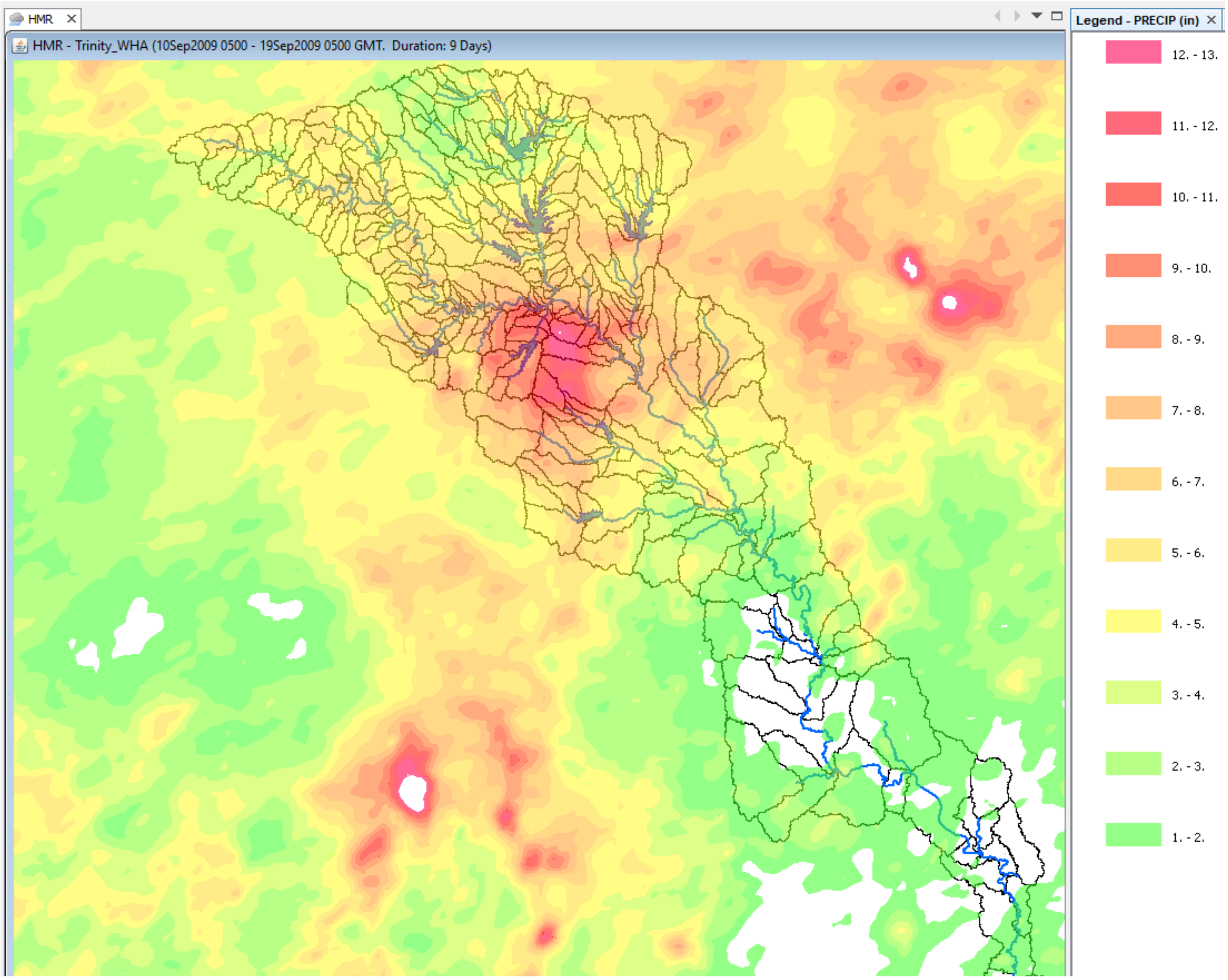


Figure 6.11: Rainfall Depths (inches) for the September 2009 Calibration Storm

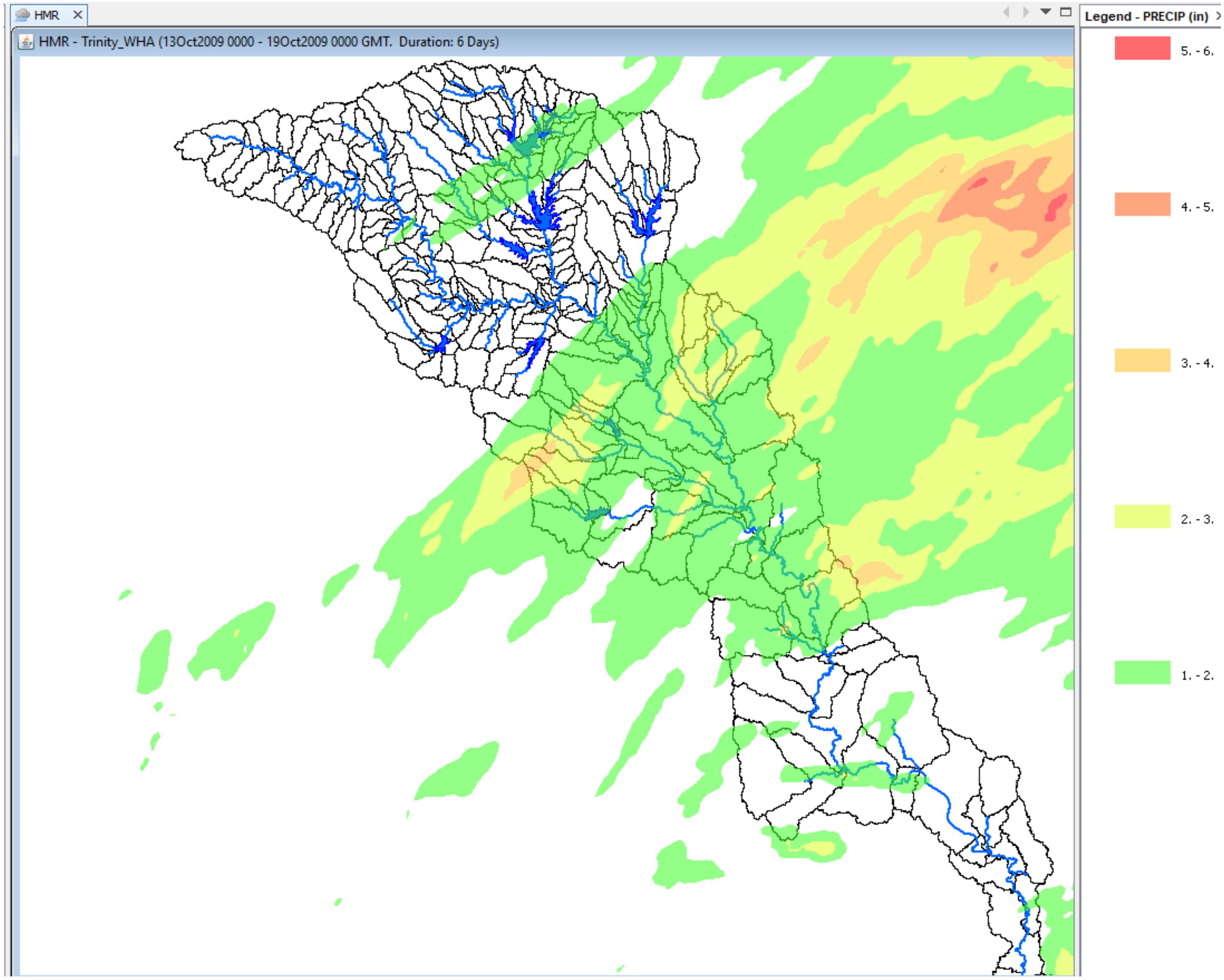


Figure 6.12: Rainfall Depths (inches) for the October 2009 Calibration Storm

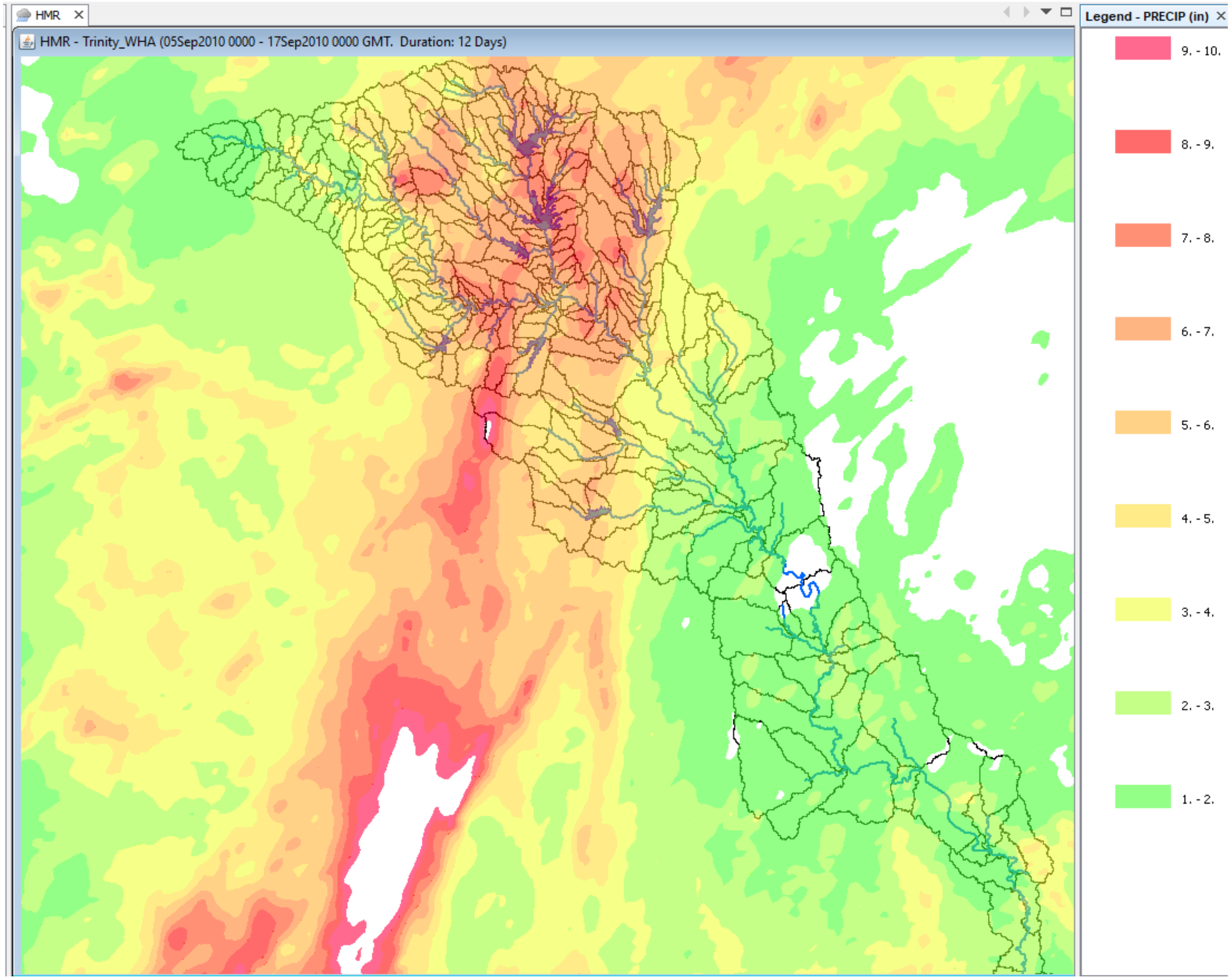


Figure 6.13: Rainfall Depths (inches) for the September 2010 Calibration Storm

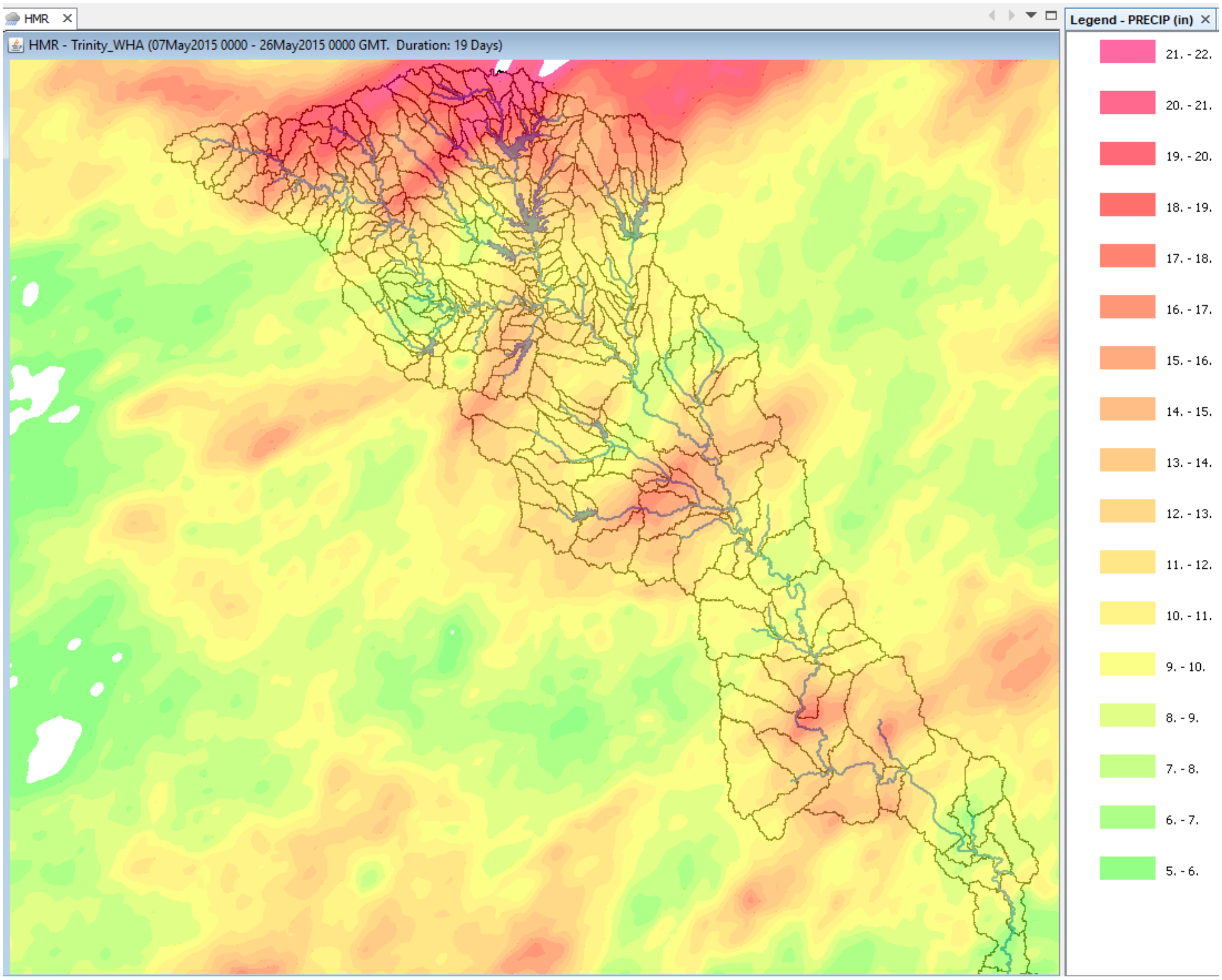


Figure 6.14: Rainfall Depths (inches) for the May 2015 Calibration Storm

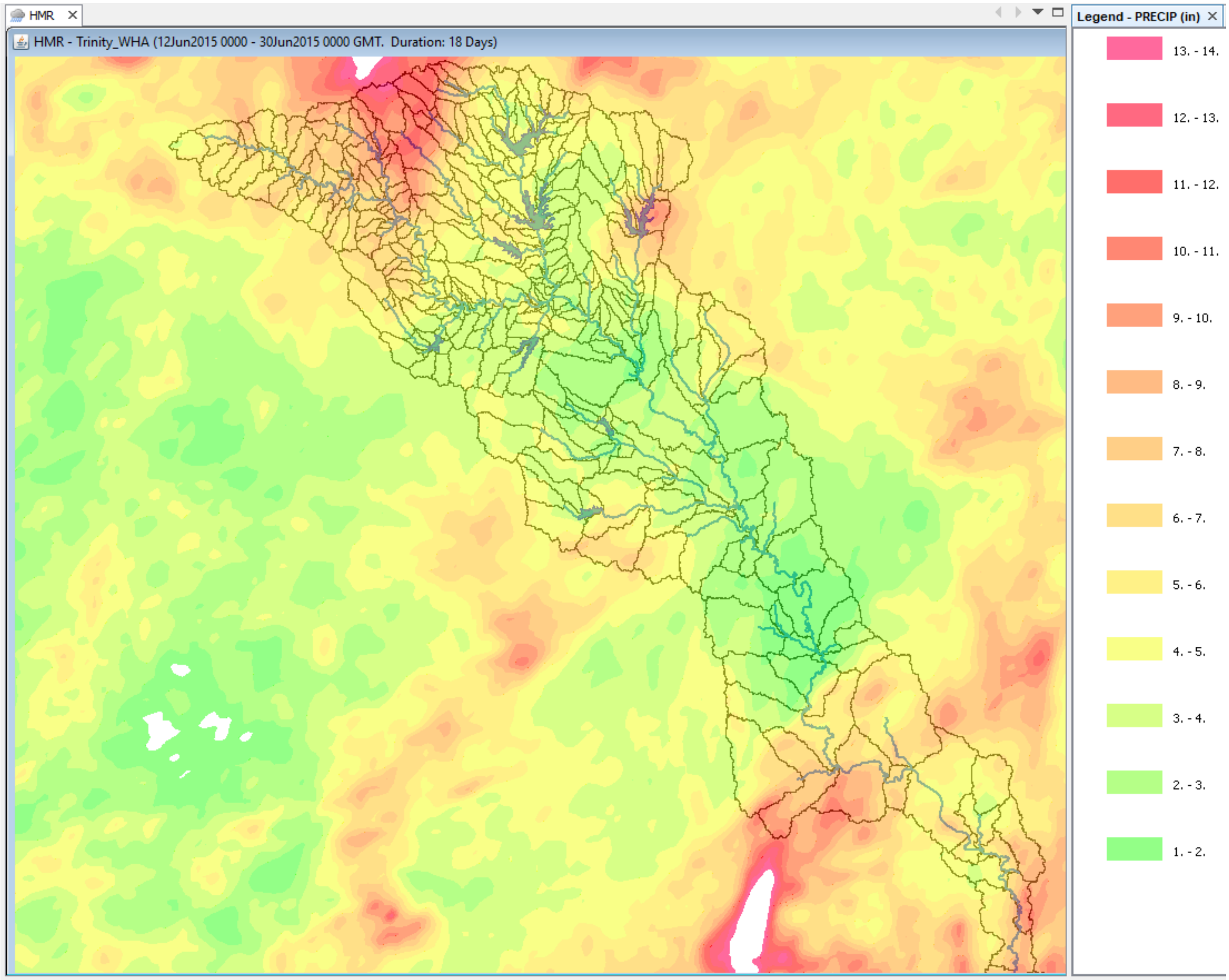


Figure 6.15: Rainfall Depths (inches) for the June 2015 Calibration Storm

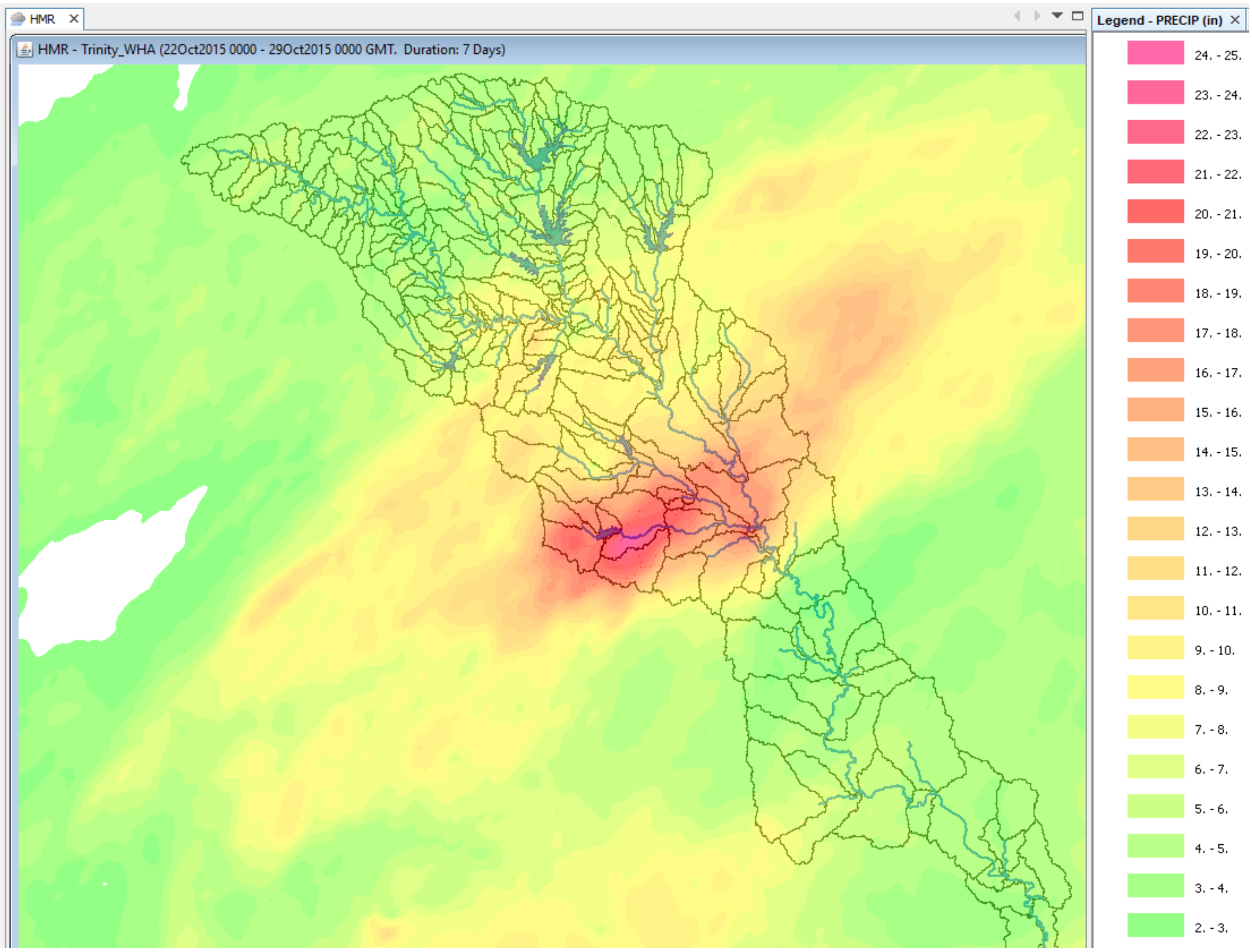


Figure 6.16: Rainfall Depths (inches) for the October 2015 Calibration Storm

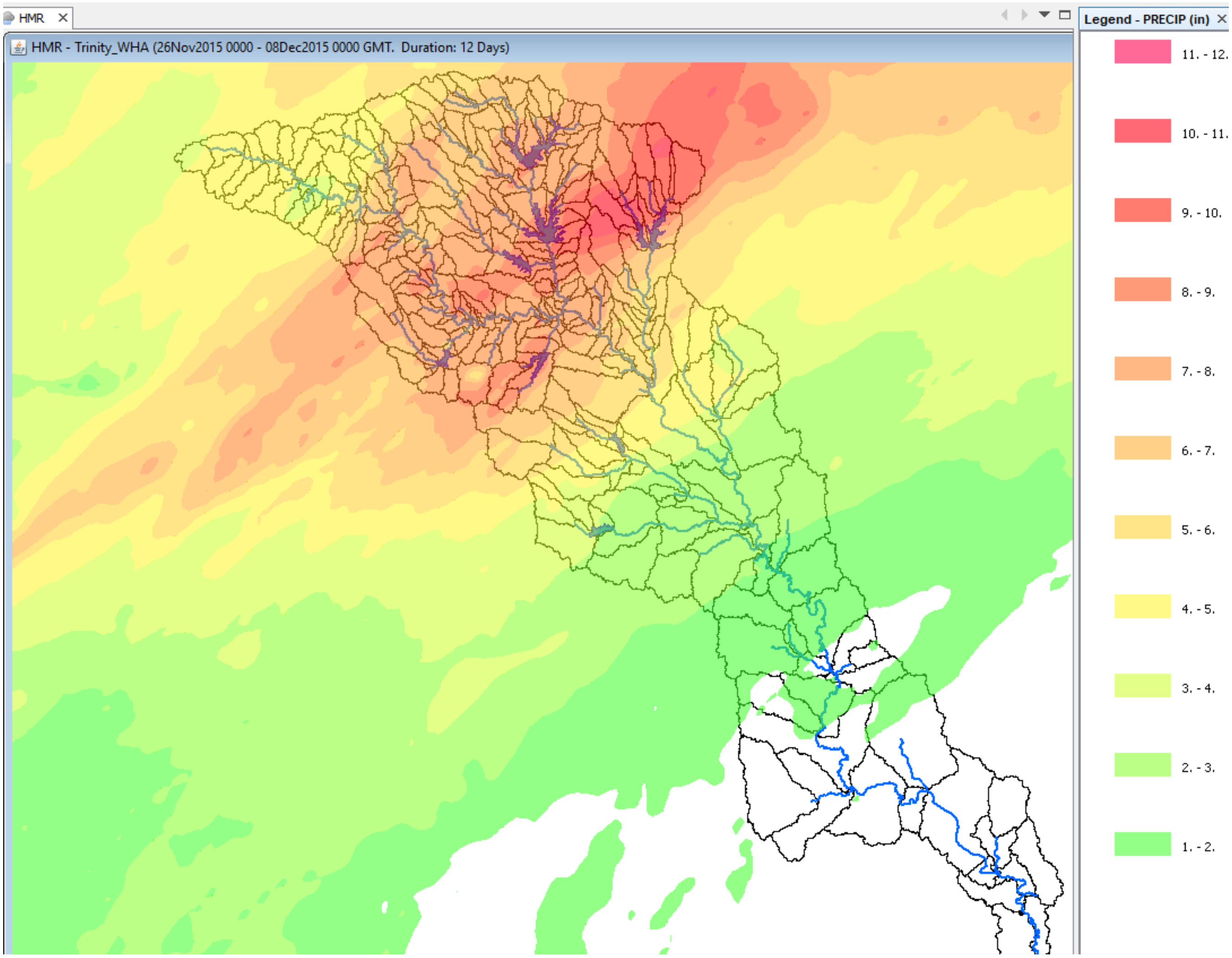


Figure 6.17: Rainfall Depths (inches) for the November 2015 Calibration Storm

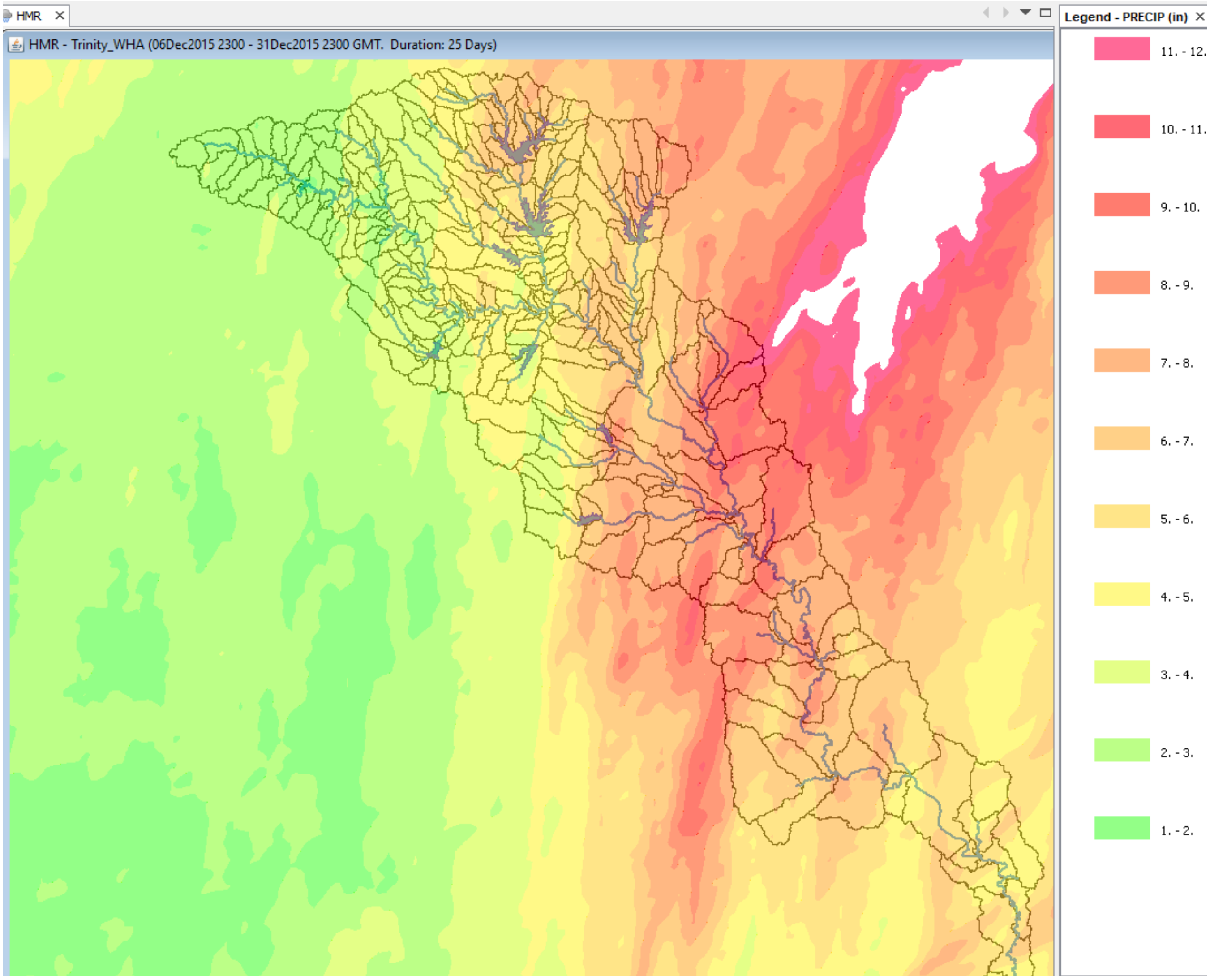


Figure 6.18: Rainfall Depths (inches) for the December 2015 Calibration Storm

Table 6.3: Calibrated Storm Events for Specific Gage Locations

USGS Gage Location	Dec-91	Apr-99	Jun-00	Jun-04	Nov-04	Oct-06	Mar-07	Jun-07	Jul-07	Sep-09	Oct-09	Sep-10	May-15	Jun-15	Oct-15	Nov-15	Dec-15
West Fork Trinity River near Jacksboro, TX				Yes			Yes						Yes	Yes		Yes	
Big Sandy Creek nr Bridgeport at Hwy 114 bridge				Yes			Yes						Yes	Yes		Yes	
West Fork Trinity River near Boyd, TX - at FM 730 bridge				Yes			Yes						Yes	Yes		Yes	
Walnut Creek at Reno, TX at FM1542 bridge in Parker County				Yes			Yes						Yes	Yes		Yes	
Marys Creek at Benbrook			Yes	Yes			Yes									Yes	
Clear Fork Trinity River at Fort Worth				Yes			Yes						Yes	Yes		Yes	
West Fork Trinity River below the Clear Fork (West Fork at Fort Worth)				Yes			Yes						Yes	Yes		Yes	
West Fork Trinity River below Sycamore Creek (West Fork Trinity River at Beach Street)				Yes			Yes						Yes	Yes		Yes	
West Fork Trinity River at Grand Prairie				Yes			Yes						Yes	Yes		Yes	
Walnut Creek near Mansfield, TX	Yes											Yes				Yes	
Mountain Ck near Venus, TX	Yes							Yes				Yes				Yes	
Elm Fk Trinity Rv at Gainesville, TX	Yes							Yes				Yes				Yes	
Timber Ck nr Collinsville, TX	Yes							Yes				Yes				Yes	
Range Creek nr Collinsville, TX	Yes							Yes				Yes				Yes	
Clear Ck nr Sanger, TX	Yes							Yes				Yes				Yes	
Little Elm Ck nr Aubrey, TX								Yes				Yes				Yes	
Doe Br at Hwy 380 nr Prosper, TX								Yes				Yes				Yes	
Hickory Creek at Denton, TX												Yes				Yes	
Indian Creek at Carrolton, TX								Yes				Yes				Yes	
Denton Creek nr Justin, TX	Yes							Yes				Yes				Yes	

USGS Gage Location	Dec-91	Apr-99	Jun-00	Jun-04	Nov-04	Oct-06	Mar-07	Jun-07	Jul-07	Sep-09	Oct-09	Sep-10	May-15	Jun-15	Oct-15	Nov-15	Dec-15
Elm Fork Trinity River near Carrollton	Yes							Yes				Yes				Yes	
Elm Fork Trinity River at Spur 348	Yes											Yes				Yes	
Trinity River at Dallas, TX	Yes							Yes				Yes				Yes	
White Rock Creek at Greenville Ave	Yes							Yes				Yes				Yes	
Trinity River below Honey Springs Branch (Trinity River below Dallas, TX)								Yes				Yes				Yes	
East Fork Trinity River near McKinney, TX								Yes					Yes			Yes	
Sister Grove Creek near Blue Ridge								Yes			Yes		Yes			Yes	
Indian Creek at SH 78 nr Farmersville, TX								Yes					Yes			Yes	Yes
Rowlett Creek near Sachse, TX								Yes					Yes			Yes	
East Fork Trinity River near Forney								Yes					Yes			Yes	
East Fork Trinity River near Crandall, TX					Yes			Yes				Yes					
Trinity River near Rosser, TX									Yes			Yes				Yes	
Kings Creek at SH34 near Kaufman, TX													Yes			Yes	Yes
Cedar Creek near Kemp, TX								Yes					Yes				Yes
Trinity River at Trinidad, TX									Yes				Yes				Yes
Chambers Creek near Rice, TX										Yes	Yes		Yes		Yes		
White Rock Creek at FM 308 near Irene, TX										Yes	Yes		Yes		Yes		
Tehuacana Creek near Streetman, TX					Yes				Yes				Yes	Yes			Yes
Trinity River near Oakwood, TX								Yes					Yes			Yes	
Upper Keechi Creek near Oakwood, TX									Yes				Yes				Yes
Trinity River near Crockett, TX									Yes				Yes			Yes	
Bedias Creek near Madisonville, TX													Yes	Yes			Yes

USGS Gage Location	Dec-91	Apr-99	Jun-00	Jun-04	Nov-04	Oct-06	Mar-07	Jun-07	Jul-07	Sep-09	Oct-09	Sep-10	May-15	Jun-15	Oct-15	Nov-15	Dec-15
Long King Creek at Livingston, TX		Yes			Yes	Yes											
Menard Creek near Rye, TX		Yes				Yes							Yes				
Trinity River at Romayor, TX								Yes					Yes			Yes	
Trinity River at Liberty, TX								Yes					Yes			Yes	

6.4.1 Calibration Methodology

Following the initial parameter estimates, calibration simulations were made using observed hourly Next-Generation Radar (NEXRAD) Stage III gridded precipitation data obtained from the West Gulf River Forecast Center (WGRFC). For each storm event, the model's calculated flow hydrographs were compared to the observed USGS stream flow data at the gages. The model's parameters were then adjusted to improve the match between the simulated and observed hydrographs for the observed events. Calibration was performed for the 17 storm events previously listed in Table 6.2. Subbasin parameters that were adjusted during calibration included the subbasins' initial and constant loss rates, lag time, peaking coefficients, and baseflow parameters. For the routing reaches, the Muskingum parameters and the Modified Puls number of subreaches were adjusted as needed.

Calibration was generally performed from upstream to downstream, with all subbasins upstream of a specific gage receiving uniform adjustments, unless specific rainfall or observed flow patterns necessitated adjusting subbasin parameters on an individual basis. Generally, subbasin parameters were adjusted in a consistent order: first baseflow parameters, then loss rates, and then lag times and peaking coefficients. Routing subreaches were the last to be adjusted. The methods of adjustment for each parameter are summarized in Table 6.4.

To the extent possible, effort was made to calibrate the model's results to the volume, timing, peak magnitude, and shape of the observed flow hydrograph. However, imperfections in the observed rainfall data and streamflow data did not always allow for a perfect match. For example, the gridded NEXRAD rainfall data from the National Weather Service was only available on an hourly basis. This meant that intense bursts of rain that occurred in 15-min or 30-min timespans might not be adequately represented in the hourly rainfall data. It also meant that even though the model was being run on a 15-min time step, the timing of the hydrographs could only be calibrated to the nearest hour. Likewise, the observed flow values at the gages are calculated indirectly from the observed stage and a limited number of flow measurements. While abundant flow measurements were usually available in the low flow range, the number and quality of USGS flow measurements were often very limited in the high flow range, leading to uncertainty in some of the observed flow hydrographs. In cases where all aspects of the observed flow hydrograph could not be calibrated simultaneously, priority was given to matching the peak flow magnitude first, followed by the peak timing, which are the aspects of model calibration that are most relevant to the 1% annual chance (100-yr) flood estimation.

Table 6.4: HEC-HMS Calibration Approach

Parameter	Calibration Approach
Baseflow Parameters	First, the baseflow parameters were adjusted to match the observed flow rates at the start and end of each calibration event. The initial discharges for the subbasins upstream of a certain gage were adjusted uniformly up or down to match the initial observed discharge at that gage. Similarly, the recession constant was adjusted to match the slope of the recession limb of the observed hydrograph, and the ratio to peak was adjusted to match the observed discharge at the end of the calibration event. All baseflow parameters were adjusted uniformly for all subbasins upstream of a given gage
Initial Loss (in)	After adjusting the baseflow parameters, the initial and constant losses were adjusted to calibrate the total volume of the flood hydrograph. The initial loss was increased or decreased until the timing and volume of the initial runoff generally matched the observed arrival of the flow hydrograph at the nearest downstream gage. All subbasins that were upstream of each gage were generally adjusted uniformly, unless specific rainfall and observed flow patterns necessitated adjusting the subbasin initial losses on an individual basis.
Constant Loss Rate (in/hr)	After adjusting the baseflow and initial loss parameters, the constant losses were adjusted to calibrate the total volume of the flood hydrograph. The subbasins' constant loss rates were increased or decreased until the volume and magnitude of the simulated hydrographs generally matched the observed volume of the flow hydrograph at the nearest downstream gage. The combination of the adjusted baseflow and loss rate parameters led to the total calibrated volume at the gage.
Lag Time (hours)	After adjusting the loss rates, the Snyder's lag times were the next parameters to be adjusted upstream of an individual gage. The Snyder's lag times were adjusted to match the timing of the observed peak flow at the gage. Normally, all of the subbasin lag times upstream of an individual gage were adjusted uniformly and proportionally to one another, unless the magnitude or shape of the observed hydrograph necessitated making individual adjustments. Efforts were also made to ensure that the adjusted lag times still fell within a reasonable range, using the lag times corresponding to 0% sand and 100% sand in the Fort Worth District regional lag time equation as a guide.
Peaking Coefficient	Peaking coefficients were adjusted to match the general shape of the observed flow hydrograph as higher peaking coefficients produce steeper, narrower flood hydrographs, and lower peaking coefficients produce flatter, wider flood hydrographs. An attempt was made to use the same peaking coefficient for all subbasins with similar watershed characteristics. For example, steep, hilly subbasins were given a higher peaking coefficient, whereas flatter subbasins, such as those near the coast, were given lower peaking coefficients. Efforts were also made to ensure that the adjusted peaking coefficients fell within the typical range of 0.4 to 0.8. In most cases, peaking coefficients were adjusted once and left alone between subsequent events.
Modified Puls Routing Subreaches	The number of subreaches in the Modified Puls routing reaches were the final parameters to be adjusted when necessary. Calibration of routing parameters focused on storms that fell near the upstream end of the watershed and were routed downstream with little intervening subbasin flow. Adjustments to the number of subreaches in a given routing reach were made in order to match the amount of attenuation in the peak flow that occurred from the upstream end of a reach to the downstream gage. In a very few cases, where an adjustment to the subreaches was not sufficient to match the observed downstream hydrograph, a factor was also applied to the reach's storage volume in the storage-discharge curve.

Parameter	Calibration Approach
Muskingum Routing Parameters	For areas of the model that included Muskingum routing, the Muskingum k, X and subreach values were adjusted as needed. Calibration of the routing parameters focused on storms that fell near the upstream end of the watershed and were routed downstream with little intervening local flow. The Muskingum k values were adjusted to match the timing of the observed peak flow at the gage, while the Muskingum X values were adjusted to match the relative flatness or steepness of the hydrograph. Finally, adjustments to the number of subreaches were made in order to match the amount of attenuation in the peak flow that occurred from the upstream end of a reach to the downstream gage.

6.4.2 Calibrated Results

The final calibration results show that the HEC-HMS model was able to accurately simulate the response of the watershed, as it reproduced the volume, timing, shape, and peak magnitudes of most observed floods very well. A sample of the calibration results is show in Figure 6.19 and Figure 6.20 but the complete set of calibration results can be found in Appendix B – Rainfall Runoff Modeling in HEC-HMS. The figures show the HEC-HMS computed versus the USGS observed flow hydrographs at each gage location. Figures are only shown for the locations where the USGS stream gages were recording for that event and where the magnitude of the flow was significant enough to warrant calibration.

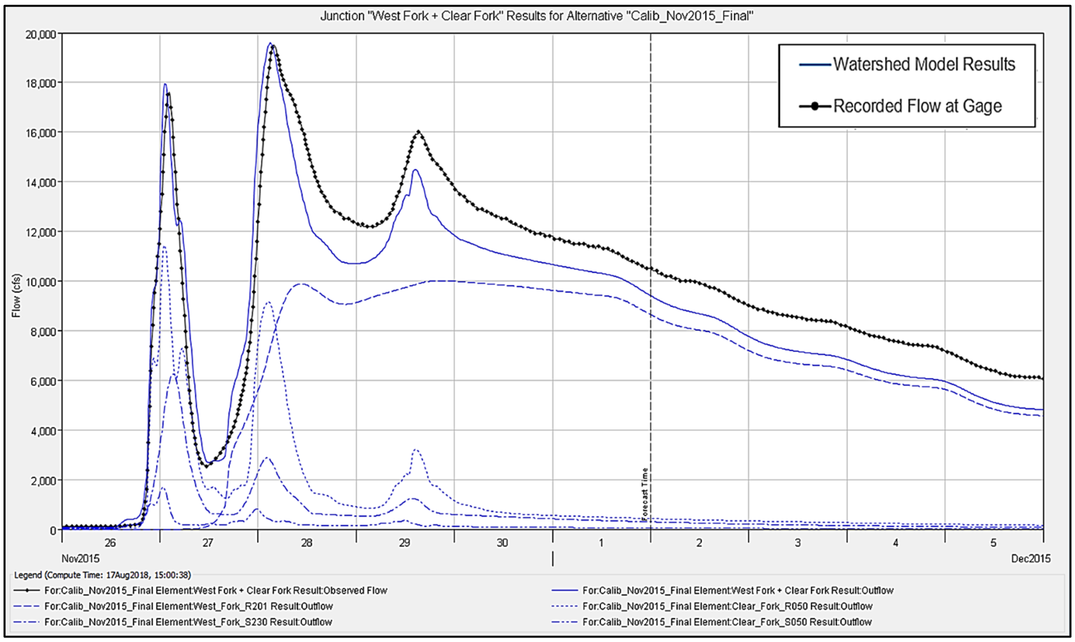


Figure 6.19: November 2014 Calibration Results for the West Fork at Fort Worth Gage

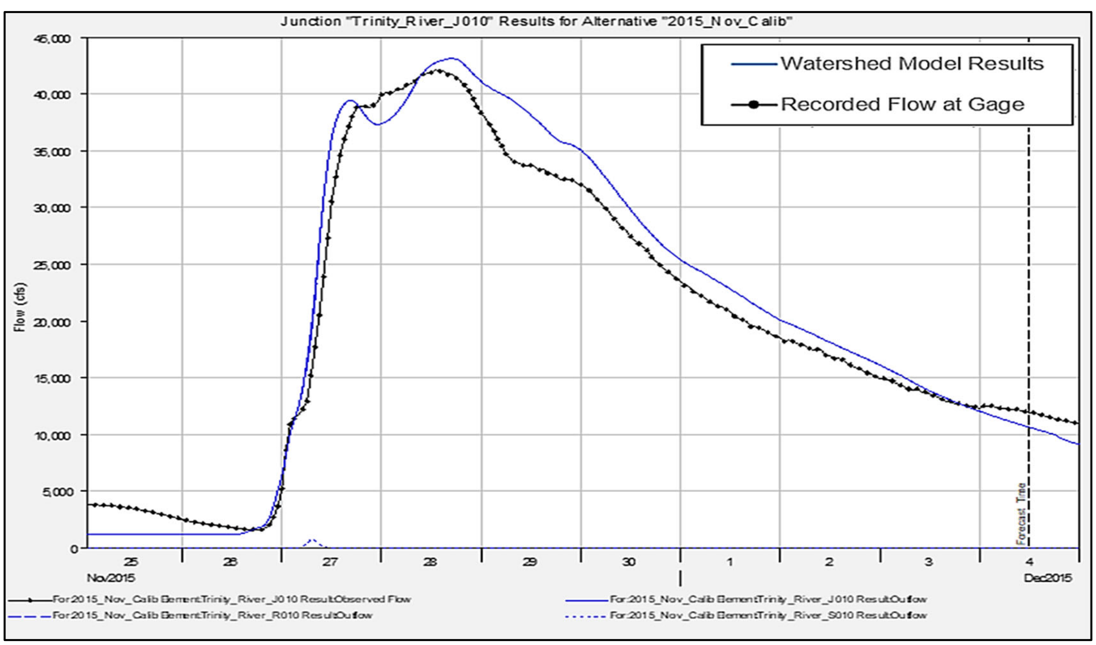


Figure 6.20: November 2015 Calibration Results for the Trinity River at Dallas Gage

6.4.3 Mary's Creek Investigation

One location that requires special mention is the Mary's Creek at Benbrook gage. This location received additional investigation following the preliminary calibration results. The investigation included a unit hydrograph peaking study performed to improve the accuracy of flood frequency estimates in the watershed by improving the unit hydrograph parameter estimates within the hydrologic modeling. There were 3 primary reasons for this investigation. The first reason is that the calibration events available for HMS model calibration were very limited and much smaller in magnitude than those used to administer the National Flood Insurance Program (NFIP) program such as the 1% annual chance (100-yr) event. The calibration events had 24-hour runoff totals between 1-2 inches, while the 1% annual chance 24-hour design runoff amount is 6+ inches for a 24-hour storm event based on the USACE Fort Worth District losses being used in this study. It is well documented in literature that more intense storm events have a more rapid and severe runoff response than smaller less intense events (Snyder; Minshall; USACE, 1991). This introduced some concern that the calibrated HEC-HMS parameters would not sufficiently represent physical watershed response to a much more intense storm event, such as the 1% annual chance event. The second reason for the additional investigation is the significant level of new development planned for this area, increasing the importance of accurate flood frequency estimates. The final reason for the investigation was the 2015 release of HEC-RAS version 5.0, which includes the ability to apply excess-precipitation onto a 2-dimensional (2D) mesh and simulate the excess-runoff being routed throughout the system with the unsteady 2D equations in HEC-RAS.

The HEC-RAS 2D model utilized 2015 Light, Detection, and Ranging (LiDAR) data obtained from the City of Fort Worth. Large culverts were field measured and added into the model to improve the models ability to route flow through significant constrictions within the watershed. The model was calibrated and validated, with there being a very small difference between the calibrated model and the uncalibrated model. The uncalibrated model resulted in a peak discharge 6% less than the calibrated model. Comparision of the hydrographs is located within Figure 4.3 of Appendix F - USACE 2-Dimensional HEC-RAS Analysis of Mary's Creek. The results of the study indicated significant peaking occurs to unit hydrograph parameters as storm intensity increases. For example, the 10% annual chance event (10-yr) lag time from the HEC-RAS 2D study was approximately 2.1 hours, while the 1% annual chance (100-y) lag time from the HEC-RAS 2D study came out to 1.5 hours. The 10% annual chance lag time of 2.1 hours matches that developed during HEC-HMS calibration of the smaller storm events, This trend is consistent with additional storm calibrations of smaller events, not performed during the original calibration effort within the watershed and is consistent with existing publications on unit hydrograph peaking.

Excess precipitation from hypothetical 24-hour storms, with an alternating block distribution was applied to the HEC-RAS 2D mesh and was routed to the watershed outlet. Within HEC-HMS, the same storm was applied and the resulting flow hydrograph was calibrated to the HEC-RAS 2D hydrograph for that event (Figure 6.21). This resulted in HEC-HMS unit hydrograph parameters that approximate the routing through the HEC-RAS 2D model representing the watershed. This process was performed for the 50% annual chance (2-yr) event to the 0.2% annual chance (500-yr) event. The resulting unit hydrograph parameters were then used to develop flood frequency estimates.

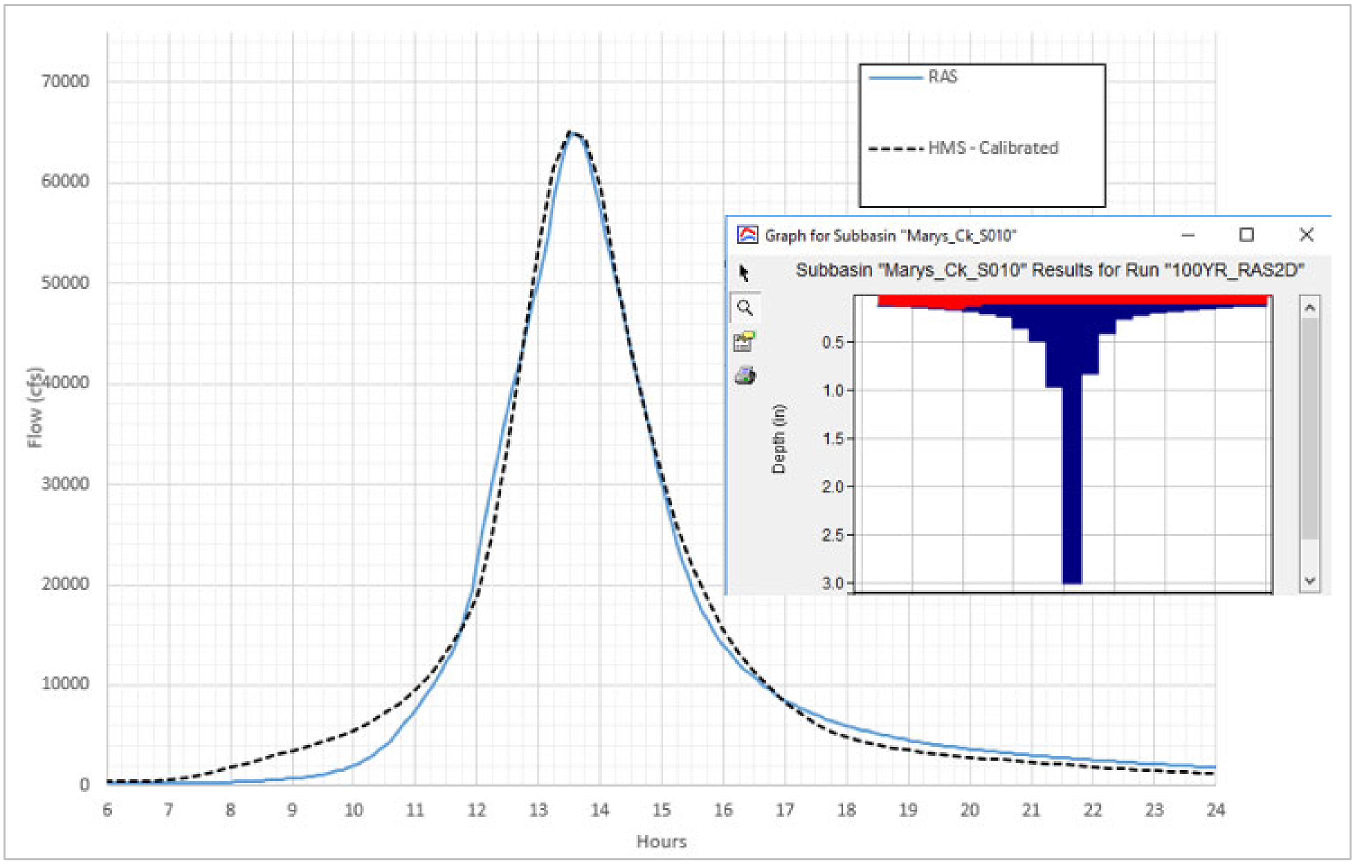


Figure 6.21: HEC-HMS Calibration to HEC-RAS 2D Results for Hypothetical Storm Events

In addition to unit hydrograph parameters specifically for the single subbasin above the Marys Creek gage, regression equations were developed for the watershed for use in future studies within the Mary's Creek watershed where additional subbasins will be added (Figure 6.22).

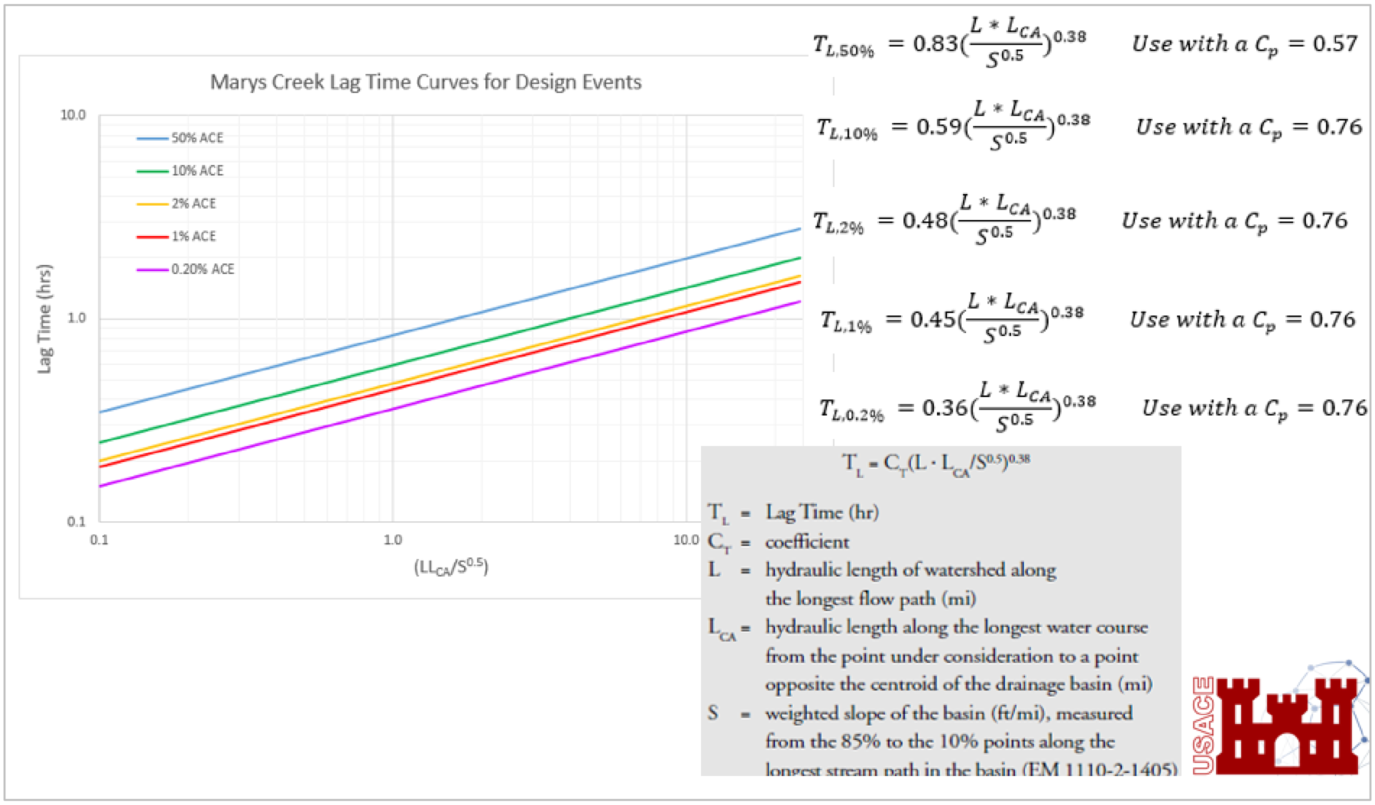


Figure 6.22. Lag Time Equations Approximating RAS 2D Routing through the Marys Creek Watershed

Oversight and review for the unit hydrograph peaking study was performed by members from the USACE Hydrologic Engineering Center (HEC) and USACE Dam Safety Modification Mandatory Center of Expertise (DSMMX). Additional information about the unit hydrograph peaking study performed within Mary's Creek can be found in Appendix F - USACE 2-Dimensional HEC-RAS Analysis of Mary's Creek.

6.5 FINAL MODEL PARAMETERS

After the initial parameter estimates were made and the calibration process was completed, the final parameters were established. The final lag times and peaking coefficients were developed by taking a weighted average of the lag times and peaking coefficients from the calibration events. The peak discharge from the subbasin for that event was used to weight the calibrated lag times. This method has the effect of granting a higher weight to the lag times that were calibrated from larger, more intense storms, and it ignores the storms that generated no runoff from a particular subbasin.

The final baseflow parameters were selected based on the results of the calibration runs. Specifically, initial flows were selected based on typical flow rates observed on each reach of the river, and the recession constant and ratio to peak were selected based on the slope and shape of the receding limb of the hydrograph at the downstream gages.

The final Mod Puls storage discharge relationships were calculated from steady flow HEC-RAS models, and the final number of subreaches were selected based on calibration to the observed attenuation of the flood hydrograph in between stream gages.

In observed storm events, the initial and constant losses vary from storm to storm according to the antecedent moisture conditions of the soil. The losses for the frequency storms were developed using the USACE Fort Worth District Method for determining losses based on percent sand (Rodman, 1977). This method produces a different set of loss rates for each storm frequency. These losses also fall well within the band of observed losses observed throughout the watershed. Some areas within the Trinity WHA model exhibit more variation in calibrated loss rates than others but the variation is present across the different soil types. For example, there are soils with high runoff potential (Group D, Clay) that have both high and low losses for each of the different events. See subbasins above Richland-Chambers reservoir as an example for soil group D. It should also be noted that while the calibration events do provide some information about observed losses, the limited number of calibration events that were used are not necessarily a complete picture of what loss rates are possible across the watershed. For the losses developed during model calibration refer to Tables 12 and 13 of Appendix B – Rainfall Runoff Modeling in HEC-HMS

The 1% annual chance intitial loss ranges from 0.75 inches (Clay) to 0.90 inches (Sand). Initial losses were increased above 0.9 inches for some subbasins to account for the storage effects of dams that were not modeled in detail within the HEC-HMS model. The 1% annual chance constant loss ranges from 0.07 inches per hour (Clay) to 0.10 inches per hour (Sand). The default initial and constant losses for the 2-yr through 10-yr storms were then adjusted for each given frequency in order to have a better correlation with the statistical frequency curves estimated from the USGS gage records. This was done because of the increased confidence level in the statistical frequency curve for the 2 through 10-yr recurrence intervals. The 25-yr losses were adjusted when needed to create a smooth transition between the 50-yr to the 10-yr values.

The complete list of calibrated subbasin parameters, calibrated routing reach parameters, and frequency losses can be found in Appendix B – Rainfall Runoff Modeling in HEC-HMS.

6.6 POINT RAINFALL DEPTHS FOR THE FREQUENCY STORMS

Frequency point rainfall depths of various durations and recurrence intervals were collected for the Trinity River basin from NOAA Atlas 14 Volume 11: Precipitation Frequency Atlas of the United States, Texas, published in 2018 (NOAA, 2018). The point rainfall depths varied by county throughout the Trinity River watershed. A precipitation depth was asssigned to each county located within the watershed. The depth was approximately taken from the center of each county. Watershed subbasins were assigned the point rainfall depth for the particular county containing the majority of that subbasin's drainage area. The complete list of precipitation tables used can be found in Appendix B – Rainfall Runoff Modeling in HEC-HMS.

The requency precipitation depths were utilized as point rainfall depths in the frequency storms for the final HEC-HMS rainfall-runoff model. The appropriate point rainfall depth table was assigned to each subbasin within the HEC-HMS frequency storm editor. The final frequency results were then computed in HEC-HMS through the depth-area analysis of the applied frequency storms.

6.7 FREQUENCY STORM RESULTS – UNIFORM RAINFALL METHOD

The frequency flow values were then calculated in HEC-HMS by applying the frequency rainfall depths to the final watershed model through a depth-area analysis. This rainfall pattern is known as the uniform rainfall method because the same rainfall depths are applied uniformly over the entire watershed. The final HEC-HMS frequency flows for significant locations throughout the watershed model can be seen in Table 6.5. These results will later be compared to elliptical shaped storm results from HEC-HMS along with existing published FEMA FIS values as well as other methods from this study.

In some cases, one may observe that the simulated discharge decreases in the downstream direction. It is not an uncommon phenomenon to see decreasing frequency peak discharges for some river reaches as flood waters spread out into the floodplain and the hydrograph becomes dampened as it moves downstream. This can be due to a combination of peak attenuation due to river routing as well as the difference in timing between the peak of the main stem river versus the runoff from the local tributaries and subbasins.

Table 6.5: Summary of Discharges (cfs) from the HEC-HMS Uniform Rainfall Method

Location Description	HEC-HMS Element Name	Drainage Area	50%	20%	10%	4%	2%	1%	0.50%	0.20%
		sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR
West Fork Trinity River below Brushy	West_Fork_J010	191.1	3,600	10,200	16,700	24,700	31,400	39,500	46,900	57,300
West Fork Trinity River at Hwy 281 (TRWB's Antelope Gage)	West_Fork_J020	231.5	3,200	10,200	17,900	27,900	36,500	46,900	56,300	69,000
West Fork Trinity River above Cameron	West_Fork_abv_CameronCk	263.3	1,600	5,600	11,200	19,600	28,100	40,100	51,300	66,200
West Fork Trinity River below Cameron	West_Fork_J030	332.4	3,600	8,800	14,000	25,400	37,100	53,300	68,100	87,700
West Fork Trinity River above Turkey	West_Fork_abv_TurkeyCk	403.1	2,300	7,600	14,200	25,200	36,800	53,600	69,200	91,700
West Fork Trinity River below Turkey	West_Fork_J050	439.2	2,600	8,100	15,000	26,500	39,000	57,200	73,900	98,300
West Fork Trinity River above Big	WestFork_abv_Big_Cleveland	549.4	2,100	6,400	11,800	20,800	30,900	47,400	63,100	86,400
West Fork Trinity River below Big	West_Fork_J070	648.1	3,600	7,100	12,400	21,200	32,000	50,700	68,400	95,400
West Fork Trinity River near Jacksboro, TX	West_Fork_J080	668.7	2,100	6,100	11,400	20,300	30,600	48,200	65,100	91,500
Lost Creek Reservoir Outflow (Lost Creek Res nr Jacksboro USGS gage)	Lost Creek Reservoir	28.8	240	890	1,600	4,500	7,200	10,200	12,700	15,900
Lost Creek above the West Fork	Lost_Ck_abv_WestFork	42.5	220	1,600	3,600	4,800	5,900	7,200	9,600	13,000
West Fork Trinity River below Lost Creek	West Fork + Lost Ck	711.2	2,200	6,400	12,000	21,300	31,600	49,600	67,100	94,500
West Fork Trinity River above Carroll	West_Fork_abv_CarrollCk	750.8	2,200	6,500	12,300	21,500	31,900	49,900	67,400	94,800
West Fork Trinity River below Carroll	West_Fork_J090	792.1	2,200	7,200	18,700	27,700	35,300	50,300	67,800	95,400
West Fork Trinity River above Beans	WestFork_abv_Beans_Ck	827.7	2,200	7,600	20,700	31,000	39,900	50,700	68,200	95,800
West Fork Trinity River below Beans	West Fork + Beans Ck	874.6	2,200	9,000	25,400	38,100	49,300	62,800	74,000	96,800
Bridgeport Reservoir Inflow	Bridgeport Inflow	1095.7	3,900	22,200	59,200	86,200	109,300	136,800	161,200	194,600
Bridgeport Reservoir Outflow	Bridgeport Reservoir	1095.7	2,700	5,500	11,700	12,700	20,400	28,800	37,700	69,200
West Fork Trinity River above Dry Creek	West_Fork_abv_DryCk	1136.2	2,500	5,500	11,700	12,800	16,600	28,900	37,900	69,400
West Fork Trinity River below Dry Creek	West_Fork_J100	1162.9	2,500	5,500	12,200	17,200	21,200	29,000	38,000	69,500
West Fork Trinity River above Big Sandy	WestFork_abv_Big_Sandy_Ck	1169.5	2,500	5,500	11,800	16,900	21,700	29,000	38,000	69,600
Amon G Carter Lake Outflow	Amon G Carter Lake	109.5	170	620	1,200	1,500	4,600	10,300	14,800	24,800
Big Sandy Creek at Route 101 bridge	Big_Sandy_Ck_J010	151.5	1,900	4,600	7,000	10,200	12,800	15,700	18,400	31,000
Big Sandy Creek above Brushy Creek	Big_Sandy_Ck_abv_Brushy_Ck	192.2	1,400	3,700	5,900	10,100	14,200	19,400	23,800	33,600
Big Sandy Creek below Brushy Creek	Big Sandy Ck + Brushy Ck	262.8	2,400	6,500	10,300	17,300	24,200	33,400	41,500	53,100
Big Sandy Creek about 2 miles upstream	Big_Sandy_Ck_J020	287.7	2,300	6,300	10,300	17,300	24,600	34,600	43,700	56,600
Big Sandy Creek nr Bridgeport USGS Gage at Hwy 114 bridge	Big_Sandy_Ck_J030	334.3	2,700	7,100	11,600	19,100	26,600	37,800	48,100	65,000

Location Description	HEC-HMS Element Name	Drainage Area	50%	20%	10%	4%	2%	1%	0.50%	0.20%
		sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR
Big Sandy Creek above the West Fork	Big_Sandy_Ck_abv_WestFork	353.9	2,500	7,000	11,200	19,000	26,700	37,900	48,400	65,400
West Fork Trinity River below Big Sandy	West Fork + Big Sandy Ck	1523.5	4,100	10,400	19,300	28,700	37,400	50,400	62,400	82,200
West Fork Trinity River at FM 3259 near Paradise, TX	West_Fork_J110	1551.8	4,000	10,200	17,100	27,300	37,400	51,100	63,700	82,600
West Fork Trinity River above Salt Creek	WestFork_abv_Salt_Ck	1573.7	3,800	9,700	15,200	24,300	33,600	47,300	59,700	78,500
West Fork Trinity River below Salt Creek	West Fork + Salt Ck	1680.4	3,800	10,000	17,100	28,500	40,700	58,900	75,700	98,800
West Fork Trinity River near Boyd, TX - USGS Gage at FM 730 bridge	West_Fork_J120	1710.8	3,600	10,000	17,000	28,500	40,600	58,700	76,400	101,100
West Fork Trinity River about 0.8 miles upstream of FM 4757 in Wise County	West_Fork_J130	1751.9	3,600	9,900	16,900	28,200	40,000	57,700	74,200	98,800
Walnut Creek at Reno, TX USGS gage at FM1542 bridge in Parker County	Walnut_Ck_J010	62.7	5,000	13,000	19,800	29,100	34,900	41,400	47,200	54,900
Walnut Creek above Eagle Mountain Lake in Tarrant County	Walnut_Ck_abv_Eagle Mountain	81.4	2,600	8,300	14,300	25,000	32,000	40,100	46,800	55,400
Eagle Mountain Reservoir Inflow	Eagle Mountain Inflow	1956.6	5,100	20,100	38,600	67,900	85,400	106,600	125,300	149,700
Eagle Mountain Reservoir Outflow	Eagle Mountain Reservoir	1956.6	3,700	7,300	14,100	19,000	23,300	30,400	38,900	56,000
Lake Worth Inflow	Lake Worth Inflow	2050.8	3,800	9,200	14,400	25,100	31,000	38,000	44,300	56,500
Lake Worth Outflow	Lake Worth	2050.8	3,500	7,400	14,300	19,300	23,400	30,700	39,200	56,400
West Fork Trinity River above the Clear Fork	WestFork_abv_Clear_Fork	2078.7	3,600	7,500	14,600	19,600	23,800	31,100	39,600	56,800
Lake Weatherford Outflow	Lake Weatherford	108.7	820	2,100	3,000	5,100	8,600	18,500	26,300	38,800
Clear Fork at Kelly Rd nr Aledo USGS gage	Clear_Fork_J010	245.1	2,100	6,200	11,000	17,600	23,100	34,800	49,700	72,100
Clear Fork above Bear Creek	Clear_Fork_abv_Bear_Ck	263.8	2,100	6,400	11,200	17,900	23,400	35,000	49,900	72,300
Benbrook Lake Inflow	Benbrook Inflow	429.2	16,300	43,700	61,600	82,500	99,100	118,000	135,900	163,700
Benbrook Lake Outflow (Clear Fork nr Benbrook)	Benbrook Lake	429.2	0	0	0	1,800	4,200	7,600	12,300	22,600
Clear Fork above Marys Creek	Clear_Fork_abv_Marys_Ck	9.4	4,300	7,800	10,000	12,500	14,300	16,200	18,100	20,800
Marys Creek at Benbrook USGS gage	Marys_Ck_S010	54.2	2,500	12,400	25,100	43,500	52,700	63,100	77,000	92,500
Clear Fork below Marys Creek	Clear Fork + Marys Creek	63.6	4,000	13,200	26,700	46,800	56,700	68,700	83,500	100,800
Clear Fork Trinity River at Fort Worth	Clear_Fork_J020	89.0	5,700	17,000	31,500	53,200	62,600	72,100	83,800	99,400
Clear Fork Trinity River above the West	Clear_Fork_abv_WestFork	93.9	6,200	17,100	30,800	50,200	59,700	69,500	80,000	93,900
West Fork Trinity River below the Clear Fork (West Fork at Fort Worth USGS gage)	West Fork + Clear Fork	2172.5	7,300	19,900	35,600	57,400	68,600	80,500	92,900	113,400

Location Description	HEC-HMS Element Name	Drainage Area	50%	20%	10%	4%	2%	1%	0.50%	0.20%
		sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR
West Fork Trinity River above Marine	WestFork_abv_MarineCk	2173.7	7,200	19,800	35,400	57,100	67,900	79,800	92,800	113,100
West Fork Trinity River below Marine Creek	West Fork + Marine Ck	2195.4	8,000	20,600	36,400	58,700	70,000	82,200	95,600	116,300
West Fork Trinity River above Sycamore Creek	West_Fork_J140	2204.6	8,300	19,800	36,100	56,900	66,300	80,600	95,700	115,800
West Fork Trinity River below Sycamore Creek (West Fork Trinity River at Beach	West_Fork_J150	2243.8	8,600	19,700	34,500	58,200	69,400	82,300	97,500	119,400
West Fork above Big Fossil	WestFork_abv_BigFossil	2256.8	7,700	17,700	31,900	55,400	67,400	80,800	95,500	117,000
West Fork Trinity River and Big Fossil Creek Confluence	West_Fork_J160	2333.4	12,900	23,800	38,000	66,200	81,300	98,300	116,800	143,600
Village Creek at Everman USGS gage	Village_Ck_S010	90.4	7,400	14,300	20,200	27,200	33,000	39,700	46,100	54,800
Lake Arlington Inflow	Lake Arlington Inflow	143.1	13,000	24,600	31,700	40,900	48,500	56,400	64,300	75,100
Lake Arlington Outflow	Lake Arlington	143.1	2,300	3,500	3,600	4,900	10,500	18,700	26,800	37,500
Village Creek above West Fork	Village_Ck_abv_WestFork	191.7	3,300	7,200	11,000	17,300	20,400	23,900	27,200	38,700
West Fork Trinity River below Village	West Fork + Village Ck	2554.0	11,900	21,300	35,600	60,400	77,400	100,300	124,600	161,100
West Fork Trinity River below Johnson Creek	West_Fork_J170	2618.6	9,000	17,700	26,500	49,100	65,600	88,400	115,000	147,600
West Fork Trinity River at Grand Prairie USGS gage	West_Fork_J180	2623.4	9,000	17,700	26,500	49,300	65,700	88,200	113,800	146,400
West Fork Trinity River above Big Bear Creek	West_Fork_abv_Big_Bear_Ck	2625.5	8,900	17,000	25,900	47,700	62,900	84,000	108,000	141,800
West Fork Trinity River below Big Bear Creek	West Fork + Bear Ck	2718.8	10,300	18,300	29,200	56,300	74,300	96,800	125,600	163,000
West Fork Trinity River above Mountain Creek	West_Fork_abv_Mountain_Ck	2727.4	10,300	18,300	28,700	52,400	70,200	92,500	117,300	154,000
Walnut Creek near Mansfield, TX USGS	Joe_Pool_S030	62.9	4,100	8,100	11,600	17,100	20,900	25,300	29,800	35,100
Walnut Creek above Joe Pool Lake	Walnut Ck + Joe Pool	67.2	4,000	7,900	11,300	16,700	20,500	25,000	29,400	34,700
Mountain Ck near Venus, TX USGS Gage	Joe_Pool_S010	26.0	3,600	6,700	8,800	11,600	13,900	16,500	18,900	22,300
Joe Pool Lake Inflow	Joe Pool Inflow	224.2	14,100	27,500	38,500	54,600	67,300	82,500	97,400	116,200
Joe Pool Lake Outflow	Joe Pool Lake	224.2	0	0	0	0	0	0	0	0
Mountain Creek Lake Inflow	Mountain Creek Inflow	70.6	20,600	32,800	40,400	50,200	57,800	66,000	74,300	85,300
Mountain Creek Lake Outflow	Mountain Creek Reservoir	70.6	11,900	21,700	29,700	40,500	48,000	56,600	63,800	69,400
Mountain Creek above the West Fork Trinity River	Mountain_Ck_abv_West_Fork	80.2	8,800	15,500	20,400	26,700	31,900	38,300	44,600	52,600

Location Description	HEC-HMS Element Name	Drainage Area	50%	20%	10%	4%	2%	1%	0.50%	0.20%
		sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR
West Fork Trinity River below Mountain Creek	West Fork + Mountain Ck	2807.6	14,400	24,800	32,500	54,100	72,000	94,400	119,600	157,500
West Fork Trinity River above the Elm Fork Trinity River	West_Fork_abv_Elm_Fork	2820.9	14,700	24,700	32,000	53,600	71,600	94,000	119,000	156,700
Elm Fork Trinity River above Brushy Elm Creek	Elm_Fork_abv_Brushy_Elm_Ck	67.4	2,600	5,200	7,900	12,800	17,700	24,100	30,500	38,900
Muenster Lake Outflow	Muenster Lake	14.0	200	330	340	360	370	510	790	1,200
Brushy Elm Creek above the Elm Fork Trinity River	Brushy_Elm_Ck_abv_Elm_Fork	25.5	1,800	3,600	4,900	6,500	7,700	9,100	10,500	12,400
Elm Fork Trinity River below Brushy Elm Creek	Elm_Fork_J010	92.9	3,300	6,800	10,000	15,600	20,800	27,500	34,500	43,800
Elm Fork Trinity River below Dry Elm	Elm_Fork_J020	137.0	6,200	13,200	19,500	28,500	36,400	45,600	54,800	67,300
Elm Fk Trinity Rv at Gainesville, TX USGS	Elm_Fork_J030	177.2	8,300	18,100	26,500	38,300	48,400	60,400	71,900	87,500
Elm Fork Trinity River below Pecan Creek	Elm Fork + Pecan Ck	216.8	8,100	18,100	27,000	39,700	50,800	64,200	77,200	94,200
Elm Fork Trinity River above Ray Roberts Lake	Elm_Fork_abv_Ray_Roberts	265.0	7,600	17,200	25,800	38,400	49,700	64,100	77,800	95,600
Lake Kiowa Inflow	Lake_Kiowa_S010	16.8	1,900	5,000	6,900	9,200	11,000	13,000	15,000	17,600
Lake Kiowa Outflow	Kiowa Lake	16.8	450	1,500	2,300	3,600	4,700	5,900	7,200	8,900
Timber Ck nr Collinsville, TX USGS gage	Timber_Ck_S010	39.0	2,600	7,500	10,800	14,900	18,200	22,000	25,600	30,500
Timber Creek above Ray Roberts Lake	Timber_Ck_abv_Ray_Roberts	64.2	4,000	10,300	15,000	20,800	25,500	31,100	36,200	43,100
Range Creek nr Collinsville, TX USGS gage	Range_Ck_S010	29.3	2,700	8,300	12,900	20,400	24,000	28,000	31,700	36,700
Range Creek above Ray Roberts Lake	Range_Ck_abv_Ray_Roberts	50.6	2,800	6,900	10,400	17,400	21,200	25,600	29,400	34,700
Ray Roberts Lake Inflow	Ray Roberts Inflow	692.6	48,000	90,200	118,800	157,300	189,000	226,700	262,400	310,800
Ray Roberts Lake Outflow (Elm Fork at Greenbelt nr Pilot Point USGS gage)	Ray Roberts Lake	692.6	0	0	0	0	210	1,100	2,000	3,200
Elm Fork Trinity River above Clear Creek	Elm_Fork_abv_Clear_Ck	36.9	1,200	4,800	9,000	12,000	14,400	17,200	19,700	23,200
Clear Creek above Bingham Creek	Clear_Ck_abv_Bingham_Ck	83.9	2,500	4,700	8,800	15,200	21,100	28,400	35,500	44,200
Clear Creek below Bingham Creek	Clear_Ck_J010	99.9	2,600	5,100	9,700	17,200	24,000	32,500	40,700	50,800
Clear Creek above Williams Creek	Clear_Ck_abv_Williams_Ck	151.6	3,200	5,300	10,100	18,600	26,800	37,300	47,300	60,000
Clear Creek below Williams Creek	Clear_Ck_J020	187.2	4,400	7,400	13,500	24,000	34,000	46,800	59,200	74,700
Clear Creek below Flat Creek	Clear_Ck_J030	214.5	4,600	8,700	16,300	28,300	39,300	53,400	67,100	84,400
Clear Creek above Duck Creek	Clear_Ck_abv_Duck_Ck	259.5	5,100	9,200	17,000	29,700	41,500	56,900	71,900	90,400
Clear Ck nr Sanger, TX USGS gage	Clear_Ck_J040	294.6	6,000	10,400	19,000	32,800	45,700	62,600	78,900	99,300

Location Description	HEC-HMS Element Name	Drainage Area	50%	20%	10%	4%	2%	1%	0.50%	0.20%
		sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR
Clear Creek above Moores Branch	Clear_Ck_abv_Moores_Br	309.9	5,600	9,500	16,500	29,500	42,500	59,700	76,300	97,200
Clear Creek below Moores Branch	Clear_Ck_J050	322.8	5,700	9,600	16,700	29,800	43,000	60,400	77,400	98,600
Clear Creek above the Elm Fork Trinity River	Clear_Ck_abv_Elm_Fork	351.2	5,300	9,100	15,800	28,900	42,500	60,600	78,300	100,600
Elm Fork Trinity River below Clear Creek	Elm Fork + Clear Ck	388.1	5,300	9,300	16,100	29,400	43,300	62,100	80,500	104,000
Little Elm Ck nr Aubrey, TX USGS gage	Little_Elm_Ck_J010	72.9	3,400	7,400	10,400	15,200	19,500	24,700	29,500	35,700
Little Elm Creek below Mustang Creek	Little_Elm_Ck_J020	95.8	4,100	8,700	12,300	18,000	23,100	29,300	35,100	42,500
Doe Br at Hwy 380 nr Prosper, TX USGS	Doe_Branch_S010	38.4	4,200	7,200	9,500	12,500	14,900	17,700	20,300	23,800
Doe Branch above Little Elm Creek	Doe_Branch_abv_Lewisville	71.0	6,500	11,600	15,400	20,700	24,800	29,600	34,000	40,100
Little Elm below Doe Branch	Doe Branch + Lewisville	231.3	8,900	17,900	24,800	34,100	41,800	51,200	60,000	72,500
Hickory Creek below North & South Hickory Creek confluence	Hickory_Ck_J010	80.7	7,700	16,400	22,600	30,000	36,000	42,700	48,800	57,200
Hickory Creek at Denton, TX USGS gage	Hickory_Ck_J030	128.9	6,200	13,600	19,100	26,400	32,700	40,300	46,900	55,800
Hickory Creek at Old Alton Rd above Lewisville Lake	Hickory_Ck_abv_Lewisville	148.9	5,900	12,500	18,000	25,200	31,700	39,400	46,600	55,900
Lewisville Lake Inflow	Lewisville Inflow	968.2	38,700	69,000	91,400	119,300	143,100	169,500	193,800	227,400
Lewisville Lake Outflow (Elm Fork nr Lewisville USGS gage)	Lewisville Lake	968.2	0	0	0	0	1,500	5,500	10,100	17,400
Elm Fork Trinity River above Indian Creek	Elm_Fork_abv_Indian_Ck	21.4	1,200	2,900	4,400	7,200	8,500	10,000	11,300	13,300
Elm Fort Trinity River below Indian Creek	Elm Fork + Indian Ck	37.5	3,000	6,200	9,200	14,400	16,900	19,700	22,300	26,000
Elm Fork Trinity River below Timber Creek	Elm Fork + Timber Ck	61.5	3,700	6,900	9,700	14,800	17,500	21,200	24,700	29,400
Elm Fork Trinity River above Denton Creek	Elm_Fork_abv_Denton_Ck	79.9	5,200	9,100	12,900	19,300	22,900	27,500	31,900	37,900
Denton Creek above FM 1655	Denton_Ck_S010	116.0	3,700	8,700	14,000	20,700	26,800	32,900	41,500	52,600
Denton Creek above Sweetwater Creek	Denton_Ck_J010	285.1	5,400	12,600	20,200	29,500	38,300	46,800	58,800	71,800
Denton Creek below Sweetwater Creek	Denton_Ck_J020	346.6	6,200	14,200	22,900	34,200	44,900	55,600	70,000	86,500
Denton Creek nr Justin, TX USGS gage	Denton_Ck_J030	400.0	4,100	9,700	16,000	26,000	35,900	47,300	62,900	81,700
Denton Creek below Oliver Creek	Denton_Ck_J040	475.3	6,100	15,500	24,100	35,400	44,600	54,800	70,100	92,700
Denton Creek above Elizabeth Creek	Denton_Ck_abv_Elizabeth_Ck	506.1	6,800	15,500	23,300	35,200	45,600	57,200	70,400	94,200
Denton Creek below Elizaveth Creek	Denton_Ck_J050	599.7	12,200	26,600	38,500	55,900	71,200	88,600	105,500	127,600
Grapevine Lake Inflow	Grapevine_Inflow	694.4	14,800	29,100	38,900	55,000	70,300	89,500	107,300	131,300
Grapevine Lake Outflow (Denton Creek nr Grapevine USGS gage)	Grapevine Lake	694.4	0	0	0	0	0	3,900	9,500	19,500

Location Description	HEC-HMS Element Name	Drainage Area	50%	20%	10%	4%	2%	1%	0.50%	0.20%
		sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR
Denton Creek above the Elm Fork Trinity River	Denton_Ck_abv_Elm_Fork	24.3	2,100	4,100	6,100	10,400	12,200	14,300	16,400	19,000
Elm Fork Trinity River near Carrollton USGS gage	Elm Fork + Denton Ck	104.2	6,700	11,700	17,100	26,700	31,500	37,200	43,200	51,200
Elm Fork Trinity River at Interstate 635	Elm_Fork_J060	143.4	11,400	17,500	21,900	30,500	36,600	43,300	50,100	59,600
Elm Fork Trinity River above Hackleberry Creek	Elm_Fork_abv_Hackberry_Ck	143.4	8,300	13,300	18,300	29,100	35,200	42,100	49,000	57,200
Elm Fk Trinity Rv at Spur 348 in Irving; TX USGS gage	Elm_Fork_J070	180.4	10,000	15,000	19,100	30,300	37,100	45,100	52,800	62,400
Elm Fork Trinity River above Bachman Branch	Elm_Fork_abv_Bachman_Branch	202.6	9,100	14,100	17,900	27,100	33,700	41,700	48,500	57,700
Bachman Lake Outflow	Bachman Lake	12.7	3,100	6,000	8,100	11,200	13,400	16,000	18,600	21,600
Bachman Branch above the Elm Fork Trinity River	Bachman_Branch_abv_Elm_Fork	14.1	1,600	3,000	4,000	5,300	6,400	7,800	9,200	11,200
Elm Fork Trinity River below Bachman Branch (at Frasier Dam USGS gage)	Elm Fork + Bachman Branch	216.7	10,000	15,600	19,200	27,500	34,400	42,600	49,600	58,900
Elm Fork Trinity River above the West Fork Trinity River	Elm_Fork_abv_West_Fork	222.8	8,100	13,400	18,100	26,800	33,700	41,800	48,800	58,700
Trinity River below the West Fork and Elm Fork confluence	West Fork + Elm Fork	3043.7	20,700	33,700	43,700	77,900	100,900	129,200	163,700	210,600
Trinity River at Dallas, TX USGS gage	Trinity_River_J010	3056.1	18,800	31,600	42,800	76,800	100,200	128,500	162,400	209,500
Trinity River at the Corinth Street bridge in Dallas, TX	Trinity_River_J020	3099.0	19,200	32,200	43,300	77,000	100,600	129,000	163,000	210,400
White Rock Creek at Greenville Ave USGS	White_Rock_Ck_S010	66.7	16,300	24,400	30,800	39,500	45,900	52,900	59,600	68,700
White Rock Lake Inflow	White Rock Inflow	95.0	13,200	20,400	25,300	33,300	39,600	46,600	53,200	62,200
White Rock Lake Outflow	White Rock Lake	95.0	9,800	15,300	19,800	26,400	31,900	38,000	43,800	51,900
White Rock Creek above the Trinity River	White_Rock_Ck_abv_Trinity_Rv	134.9	9,100	16,300	20,800	26,100	30,400	35,000	39,600	46,100
Trinity River below White Rock Creek	Trinity River + White Rock	3233.9	23,400	38,200	51,300	78,800	103,500	134,300	167,800	218,800
Trinity River below Honey Springs Branch (Trinity River below Dallas, TX USGS gage)	Trinity_Rv + Honey_Springs	3256.5	23,400	38,300	51,400	78,900	103,500	134,300	167,800	219,000
Trinity River below Five Mile Ceek	Trinity_River + Five_Mile_Ck	3328.8	22,200	36,900	49,800	78,200	102,100	132,400	164,300	213,200
Trinity River above Ten Mile Creek	Trinity_River_abv_Tenmile_Ck	3367.7	20,600	31,500	43,300	70,800	95,100	120,500	148,800	189,900
Trinity River below Ten Mile Creek	Trinity River + Tenmile Ck	3469.8	20,800	32,100	44,000	71,700	96,200	121,900	150,400	191,900
Trinity River above the East Fork Trinity River	Trinity_River_abv_East_Fork	3529.4	20,300	30,200	40,200	68,200	91,200	119,700	145,700	185,300
East Fork Trinity River below Honey Creek	East_Fork+Honey_Ck	167.9	4,100	7,600	11,300	17,700	23,600	31,000	38,000	47,200
East Fork Trinity River near McKinney, TX USGS gage	East_Fork_nr_McKinney	190.1	4,600	8,500	12,500	19,300	25,600	33,800	41,400	51,400

Location Description	HEC-HMS Element Name	Drainage Area	50%	20%	10%	4%	2%	1%	0.50%	0.20%
		sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR
East Fork Trinity River above Wilson Creek	East_Fork_abv_Wilson_Ck	214.8	4,600	8,600	12,500	19,100	25,300	33,500	41,200	51,400
East Fork Trinity River below Wilson Creek	East_Fork + Wilson_Ck	292.3	7,100	12,600	18,000	26,700	34,800	45,500	55,500	68,900
Sister Grove Creek near Blue Ridge USGS	Sister_Grove_S010	83.2	1,400	2,800	4,100	6,400	8,400	11,000	13,400	16,500
Sister Grove Creek above Indian Creek	Sister_Grove_abv_Indian_Ck	121.2	2,400	4,600	6,400	8,900	11,000	13,500	15,900	19,600
Indian Creek at SH 78 nr Farmersville, TX USGS gage	Indian_Ck_S010	104.6	2,400	4,200	6,000	8,800	11,200	14,300	17,300	21,200
Indian Creek below Pilot Grove Creek	Indian_Ck + Pilot_Grove_Ck	205.8	4,400	8,800	12,600	18,400	23,400	29,800	35,800	43,800
Indian Creek above Sister Grove Creek	Indian_Ck_abv_Sister_Grove	235.9	4,700	9,300	13,300	19,500	24,900	32,100	38,600	47,300
Indian Creek below Sister Grove Creek	Sister Grove + Indian Ck	357.1	6,200	12,300	17,600	26,200	33,800	44,100	53,500	66,100
Lavon Lake Inflow	Lavon Inflow	768.2	20,300	35,200	47,100	64,200	78,700	100,800	121,900	150,500
Lake Lavon Outflow	Lavon Lake	768.2	0	0	0	0	6,200	14,600	24,800	51,800
Rowlett Creek near Sachse, TX USGS	Rowlett_Ck_S010	119.9	13,500	25,400	35,200	46,600	54,600	63,600	72,100	83,800
Ray Hubbard Lake Inflow	Ray Hubbard Inflow	301.8	24,600	42,200	56,900	75,600	90,300	107,300	123,300	145,100
Ray Hubbard Lake Outflow (East Frk blw Ray Hubbard Data)	Ray Hubbard Reservoir	301.8	8,900	16,500	26,000	38,000	47,400	59,800	83,300	101,300
East Fork Trinity River near Forney USGS	East_Fork_nr_Forney	349.9	10,500	19,500	30,300	44,100	55,000	69,300	95,500	117,100
East Fork Trinity River above Buffalo	East_Fork_abv_Buffalo_Ck	359.5	9,300	17,800	26,500	40,800	52,700	67,400	91,700	115,500
East Fork Trinity River below Buffalo	East_Fork + Buffalo_Ck	393.9	9,900	18,900	28,300	42,900	55,800	71,900	97,900	123,600
East Fork Trinity River above South Mesquite Creek	East_Fork_abv_S_Mesquite_Ck	416.9	7,700	15,500	24,000	36,000	48,100	64,000	82,200	111,600
East Fork Trinity River below South Mesquite Creek	East_Fork+South_Mesquite_Ck	446.4	8,100	16,300	25,200	37,500	50,300	67,000	86,800	117,600
East Fork Trinity River above Mustang Creek	East_Fork_abv_Mustang_Ck	465.5	8,000	15,100	23,000	32,600	43,400	57,200	72,200	96,100
East Fork Trinity River near Crandall, TX USGS gage	East_Fork_nr_Crandall	484.8	8,200	15,500	23,500	33,200	44,300	58,400	73,900	98,300
East Fork Trinity River above the Trinity River	East_Fork_abv_Trinity_River	484.8	8,000	14,100	20,600	28,700	37,100	48,600	59,700	75,100
Trinity River below the East Fork Trinity River	Trinity River + East Fork	4014.2	28,300	43,400	58,200	95,900	126,700	166,200	202,000	254,900
Trinity River below Red Oak Creek	Trinity_River + Red_Oak_Ck	4245.5	30,100	53,800	70,600	97,300	128,500	168,600	205,000	258,700
Trinity River near Rosser, TX USGS gage	Trinity_River_nr_Rosser	4349.6	27,200	40,600	54,900	91,600	126,100	166,200	200,800	253,900
Trinity River above Cedar Creek	Trinity_River_abv_Cedar_Ck	4349.6	26,100	39,600	53,900	72,500	101,900	154,800	190,400	246,400
Kings Creek at SH34 near Kaufman, TX USGS gage	Kings_Ck_nr_Kaufman	222.6	3,800	7,400	10,500	15,300	19,900	25,900	31,500	39,500

Location Description	HEC-HMS Element Name	Drainage Area	50%	20%	10%	4%	2%	1%	0.50%	0.20%
		sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR
Kings Creek above Cedar Creek Reservoir	Kings_Ck_abv_Cedar_Ck_Inflow	343.1	6,000	10,600	15,000	22,600	29,200	37,200	45,200	56,200
Cedar Creek near Kemp, TX USGS gage	Cedar_Ck_nr_Kemp	190.1	5,400	8,400	10,900	14,600	17,100	22,200	27,100	34,100
Cedar Creek above Cedar Creek Reservoir	Cedar_Ck_abv_Cedar_Ck_Inflow	283.5	5,900	11,600	16,300	22,400	27,500	33,800	39,700	48,000
Cedar Creek Reservoir Inflow	Cedar Creek Inflow	1010.8	30,300	61,600	88,900	129,700	163,900	204,900	245,300	301,600
Cedar Creek Reservoir Outflow	Cedar Creek Reservoir	1010.8	21,700	42,300	57,900	81,700	106,500	126,600	133,800	145,600
Trinity River below Cedar Creek	Trinity River + Cedar Creek	5360.4	28,200	43,200	60,200	78,600	114,600	174,100	220,200	295,100
Trinity River at Trinidad, TX USGS gage	Trinity_River_at_Trinidad	5759.3	28,000	43,300	59,800	86,700	112,400	168,400	209,900	286,400
Trinity River above Richland Creek	Trinity_Rv_abv_Richland_Ck	6042.8	28,100	43,800	60,200	82,600	107,600	167,700	211,800	286,800
Waxahachie Creek at Waxahachie	Waxahachie_Ck_S010	60.4	1,500	4,400	8,900	15,500	20,900	27,500	34,000	42,800
Lake Waxahachie Outflow	Lake Waxahachie	30.6	1,700	3,900	5,900	8,700	12,000	15,600	17,400	26,400
Waxahachie Creek below Lake Waxahachie	Waxahachie Ck+Lk Waxahachie	91.0	2,600	6,400	11,700	19,400	25,500	33,500	42,000	52,000
Mustang Creek above Bardwell Lake	Mustang_Ck_S010	29.9	3,600	6,600	8,700	11,600	14,000	16,700	19,400	23,200
Bardwell Lake Inflow	Bardwell Inflow	174.4	9,200	16,700	22,000	29,200	35,200	42,300	49,400	62,400
Bardwell Lake Outflow	Bardwell Lake	174.4	0	0	1,100	3,500	5,400	8,000	10,600	14,300
Chambers Creek below North Fork and South Fork Chambers Creek	Chambers_Ck_J010	308.4	11,000	20,600	29,700	41,200	53,900	69,700	84,700	104,400
Chambers Creek below Mill Creek	Chambers_Ck_J020	511.9	11,600	21,700	31,700	47,100	66,400	93,100	118,200	153,600
Chambers Creek below Waxahachie	Chambers Ck + Waxahachie Ck	621.0	11,300	21,400	31,400	46,300	65,900	94,400	122,600	162,500
Chambers Creek near Rice, TX USGS gage	Chambers_Ck_J030	650.1	11,200	21,300	29,900	46,200	65,600	90,900	119,500	159,000
White Rock Creek at FM 308 near Irene, TX USGS gage	Navarro_Mills_S010	65.8	3,600	8,100	12,400	19,000	24,600	31,300	37,800	46,300
Navarro Mille Lake Inflow	Navarro Mills Inflow	319.9	11,600	23,900	34,200	49,900	63,200	79,900	96,100	121,700
Navarro Mills Lake Outflow	Navarro Mills Lake	319.9	0	0	0	0	1,400	4,800	8,200	15,000
Richland Creek below Pin Oak Creek	Richland_Ck_J010	395.0	12,700	26,700	39,700	60,700	78,700	100,800	123,100	155,900
Richland Chambers Reservoir Inflow	Richland-Chambers Inflow	1465.5	27,000	52,500	74,900	111,000	143,000	183,400	223,200	281,800
Richland Chambers Reservoir Outflow	Richland-Chambers Reservoir	1465.5	10,200	21,600	34,300	63,700	93,800	136,200	177,300	234,700
Trinity River below Richland Creek	Trinity River + Richland Ck	7508.3	35,500	61,900	86,500	133,000	178,600	247,900	303,700	380,800
Trinity River above Tehuacana Creek	Trinity_Rv_abv_Tehuacana_Ck	7508.3	35,200	61,200	85,800	131,200	176,500	243,400	301,300	377,400
Tehuacana Creek near Streetman, TX USGS gage	Tehuacana_Ck_nr_Streetman	141.3	7,100	15,000	20,400	34,100	43,700	55,100	66,200	81,900
Tehuacana Creek above the Trinity River	Tehuacana_Ck_abv_Trinity_Rv	386.4	7,900	15,100	22,400	38,200	52,900	72,500	91,900	118,800

Location Description	HEC-HMS Element Name	Drainage Area	50%	20%	10%	4%	2%	1%	0.50%	0.20%
		sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR
Trinity River below Tehuacana Creek	Trinity River + Tehuacana Ck	7894.7	35,600	62,500	87,900	135,300	183,600	256,200	332,100	436,300
Trinity River above Big Brown Creek	Trinity_Rv_abv_Big_Brown_Ck	7965.3	35,600	62,400	87,900	134,900	182,000	253,300	326,700	431,700
Trinity River below Big Brown Creek	Trinity River + Big Brown Ck	8001.5	35,700	62,600	88,200	135,500	183,800	254,600	330,900	437,500
Trinity River above Catfish Creek	Trinity_River_abv_Catfish_Ck	8306.6	35,900	63,600	89,700	136,500	186,400	265,000	350,100	467,800
Trinity River below Catfish Creek	Trinity_River + Catfish_Ck	8353.0	35,900	63,700	89,800	136,800	187,000	266,800	352,900	472,100
Trinity River near Oakwood, TX USGS gage	Trinity_River_nr_Oakwood	8593.0	35,700	62,700	86,400	126,100	164,600	261,200	327,200	438,500
Trinity River above Upper Keechi Creek	TrinityRv_abv_UpperKeechi_Ck	8849.7	33,700	57,500	80,300	122,100	153,600	201,400	269,200	359,700
Upper Keechi Creek near Oakwood, TX USGS gage	Upper_Keechi_Ck_nr_Oakwood	150.3	3,400	11,400	19,500	31,100	39,200	48,900	58,300	72,000
Upper Keechie Creek above Buffalo Creek	UpperKeechi_Ck_abv_BuffaloCk	186.8	3,000	10,500	18,000	29,100	37,200	47,100	56,800	70,900
Upper Keechie Creek below Buffalo Creek	Upper_Keechi_Ck+Buffalo_Ck	459.5	5,800	21,000	35,000	54,400	69,900	89,300	109,400	135,700
Upper Keechie Creek above the Trinity River	UpperKeechi_Ck_abv_TrinityRv	509.2	5,700	20,100	33,400	51,900	66,900	86,100	106,000	132,200
Trinity River below Upper Keechi Creek	Trinity River + Upper Keechi	9358.9	33,900	58,100	81,500	124,000	156,500	208,600	279,100	373,400
Trinity River above Big Elkhart Creek	Trinity_Rv_abv_Big_Elkhart	9359.5	33,900	57,900	81,300	124,000	156,400	208,100	278,300	372,500
Houston County Lake Ouflow	Houston County Lake	48.0	110	220	420	900	1,600	4,700	7,900	12,700
Big Elkhart Creek above the Trinity River	Big_Elkhart_abv_Trinity_Rv	143.0	2,000	6,500	10,000	14,700	18,900	25,300	33,100	43,500
Trinity River below Big Elkhart Creek	Trinity River+ Big Elkhart	9502.5	33,900	58,000	81,700	124,500	157,300	209,800	280,500	375,100
Trinity River near Crockett, TX USGS gage	Trinity_River_nr_Crockett	9615.0	34,000	58,100	81,900	124,900	157,800	210,600	281,500	376,400
Trinity River above Lower Keechi Creek	Trinity_Rv_abv_LowerKeech_Ck	9791.7	34,000	53,700	71,100	116,900	149,600	189,200	252,500	342,700
Trinity River below Lower Keechi Creek	Trinity_River+LowerKeechi_Ck	9979.3	34,000	53,700	71,200	117,100	149,900	190,000	253,700	344,400
Trinity River above Bedias Creek	Trinity_River_abv_Bedias_Ck	10374.3	36,400	52,700	70,200	114,800	147,400	186,200	246,300	336,500
Bedias Creek near Madisonville, TX USGS	Bedias_Ck_S010	330.6	8,200	16,200	24,400	38,000	47,500	65,100	82,300	105,800
Bedias Creek above the Trinity River	Bedias_Ck_abv_Trinity_River	604.3	11,900	25,800	38,600	59,000	74,700	100,900	126,500	162,400
Trinity River below Bedias Creek	Trinity River + Bedias Ck	10978.5	38,000	71,100	98,700	136,000	161,300	200,700	250,000	341,400
Trinity River at Riverside, TX USGS gage	Trinity River_at_Riverside	11306.7	34,000	63,500	81,400	128,400	157,500	202,600	251,500	341,000
Lake Livingston Inflow	Lake Livingston Inflow	12301.1	67,800	119,800	161,500	221,900	276,400	346,400	418,100	523,500
Lake Livingston Outflow	Lake Livingston	12301.1	35,400	74,000	94,600	130,100	179,200	248,200	316,400	415,400
Trinity River above Long King Creek	Trinity_Rv_abv_Long_King_Ck	12340.5	35,300	73,500	94,200	126,500	171,000	235,800	301,400	396,700
Long King Creek at Livingston, TX USGS	Long_King_Ck_S010	141.1	5,700	13,600	19,700	28,700	36,500	46,300	55,800	69,400
Long King Creek above the Trinity River	Long_King_Ck_abv_Trinity_Rv	226.4	7,500	17,000	25,000	37,300	48,200	62,000	75,200	94,300
Trinity River at Goodrich, TX USGS gage	Trinity River + Long King Ck	12566.9	36,100	75,700	96,500	129,300	176,300	245,800	315,500	416,000

Location Description	HEC-HMS Element Name	Drainage Area	50%	20%	10%	4%	2%	1%	0.50%	0.20%
		sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR
Trinity River above Menard Creek	Trinity_River_abv_Menard_Ck	12628.0	36,100	69,100	85,900	107,800	137,000	184,600	244,400	337,600
Menard Creek near Rye, TX USGS gage	Menard_Ck_S010	148.1	2,300	6,300	10,000	15,600	20,800	27,900	34,700	44,400
Trinity River below Menard Creek	Trinity River + Menard Ck	12776.2	37,000	69,900	86,600	108,900	137,300	186,900	246,900	338,900
Trinity River at Romayor, TX USGS gage	Trinity_River_at_Romayor	12873.7	37,500	69,200	85,700	108,000	136,900	185,000	245,100	338,400
Trinity River near Moss Hill, TX	Trinity_River_nr_MossHill_TX	12945.7	36,800	67,200	84,200	105,900	136,400	184,700	244,700	337,600
Trinity River at Liberty, TX USGS gage	Trinity_River_at_Liberty	13176.5	33,000	66,000	84,100	106,300	136,500	185,200	245,500	338,600
Trinity River at Wallisville, TX USGS gage	Trinity Bay	13618.4	32,300	61,800	80,900	104,800	135,000	185,700	246,400	339,700

7 Elliptical Frequency Storms in HEC-HMS

7.1 INTRODUCTION TO ELLIPTICAL STORMS

Observations of actual storm events show that average precipitation intensity decreases as the area of a storm increases. The uniform rainfall method results (Section 6.7) use the depth-area analysis in HEC-HMS to produce frequency peak flow estimates (Version 4.2.1; USACE, 2014). The depth-area analysis in HEC-HMS applies the appropriate depth-area reduction factor to the given point rainfall depths based on the drainage area at a given evaluation point, which are derived from the published depth-area reduction factors from Figure 7.1 of the National Weather Service TP-40 publication (Hershfield, 1961), as shown in the figure below.

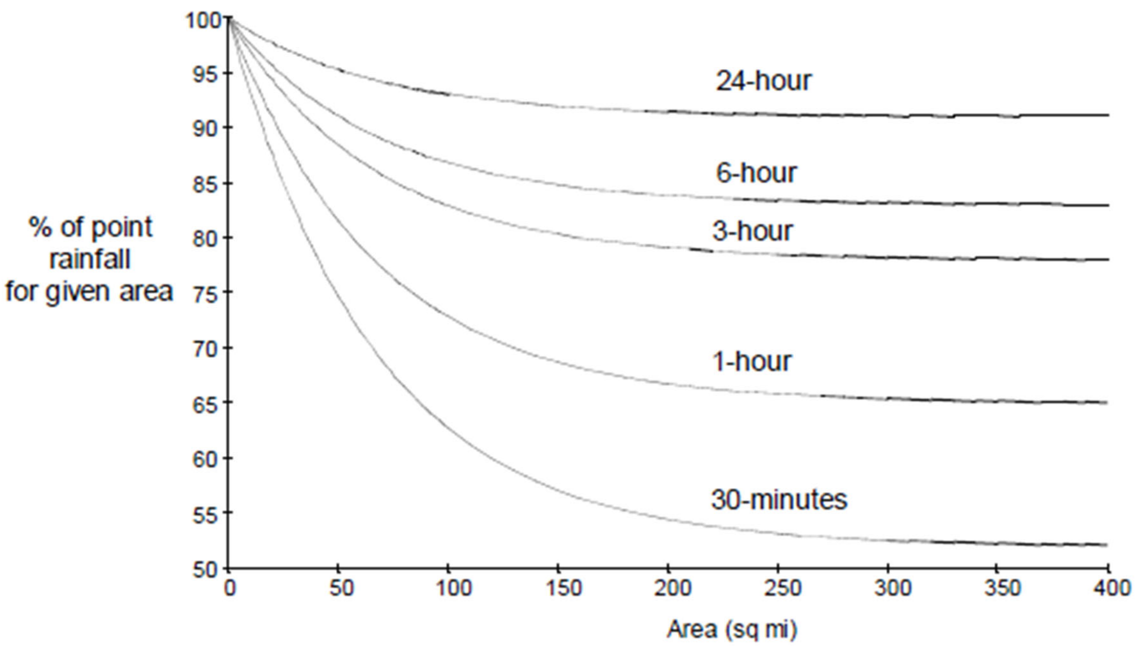


Figure 7.1: Published Depth-Area Reduction Curves from TP-40

When evaluating a point with a drainage area greater than 400 square miles, the HEC-HMS software issues a warning that the NWS depth-area reduction factors do not support storms beyond 400 square miles, as seen in the figure above. The program will still calculate the peak discharge, but the warning implies that the calculated volume of the storm may not be appropriate for larger drainage areas.

Since the Trinity hydrology study involves calculating frequency discharges for points with up to several thousand square miles of drainage area, the InFRM team developed elliptical frequency storms for points with drainage areas greater than 400 square miles. In these elliptical frequency storms, the same point rainfall depths and durations were applied as in the uniform rainfall method of Chapter 6, but the spatial distribution of the rainfall varied in an elliptical shaped pattern with higher rainfall amounts in the center of the ellipse and lesser amounts towards the outer fringes.

Elliptical shaped storms have been used in a variety of hypothetical design applications, including the Probable Maximum Precipitation (PMP) storms from Hydrometeorological Report No 52 (HMR 52) (Hansen, 1982). The elliptical frequency storms constructed for this study are similar to those of HMR 52 in that concentric ellipses are used to construct the storm's spatial pattern, and the storm's location is optimized over the watershed by identifying the storm center location and the angle of its major axis that lead to the highestpeak flow at a downstream junction of interest. Figure 7.2 shows an example of an elliptical 1% annual exceedance probability (100-yr) storm that was centered over the watershed above the Trinity River at Dallas junction. This storm is located such that the majority of the rain falls below the USACE flood control reservoirs, thus optimizing the peak flow of the Trinity River at Dallas.

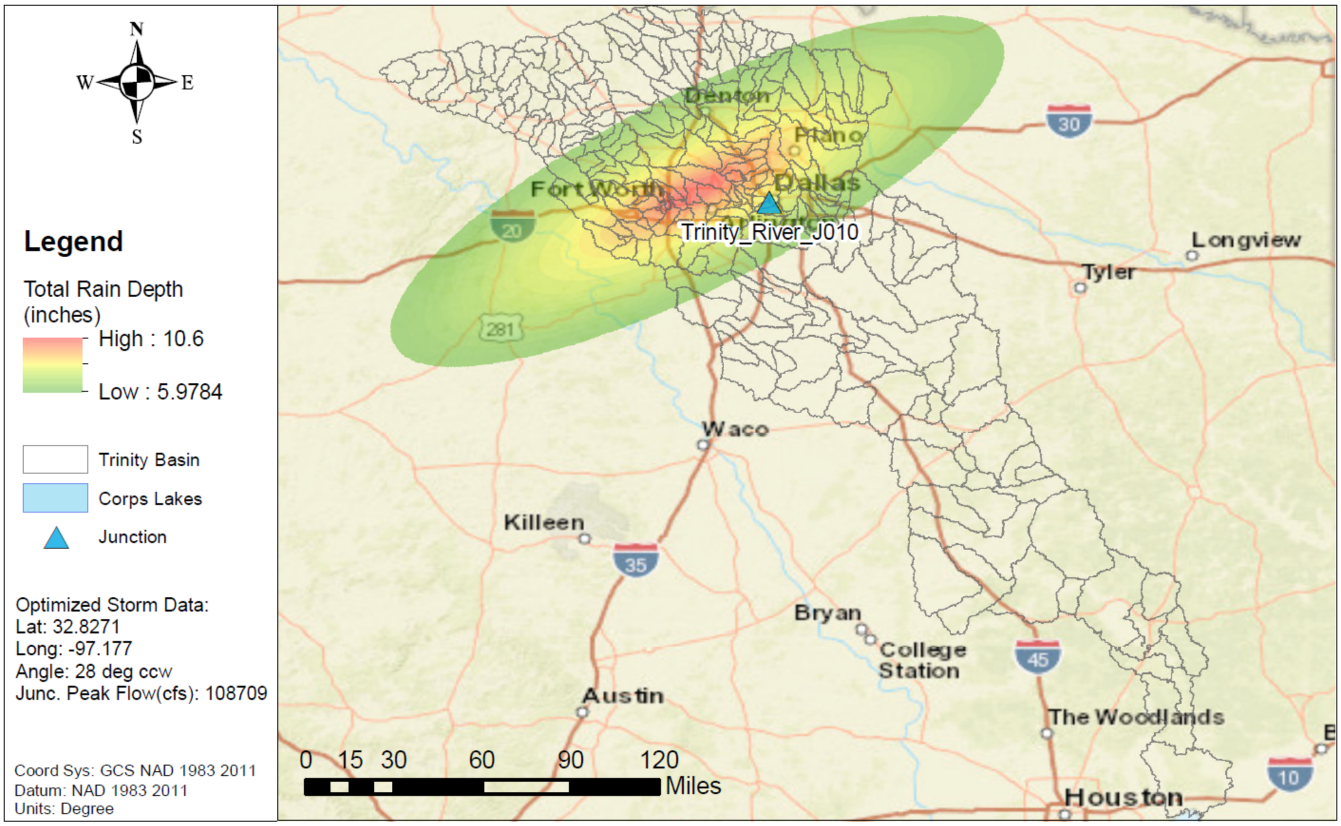


Figure 7.2: Example 1% AEP (100-yr) Elliptical Frequency Storm

7.2 ELLIPTICAL STORM PARAMETERS AND METHODOLOGY

The following elliptical storm parameters in sections 7.2.1 through 7.2.5 are relevant for the majority of the Trinity Basin. From the upper reaches of the Trinity Basin all the way downstream to the Trinity River near Crockett, TX USGS gage (128 junctions of interest), the orography and the meteorology remain relatively constant and these storm parameters worked well. However, for the 15 junctions of interest below the Crockett USGS gage, the meteorology rapidly changes and a few adjustments to the elliptical storm parameters and methodology were needed. The slightly different approach for the lower Trinity Basin is discussed in section 7.2.6.

Figure 7.3 below, summarizes the general approach used to create elliptical storms for the majority of the basin. The magnitude of the total storm is based off of one NOAA Atlas 14 point frequency depth queried from the storm center which is multipled by depth area reduction (DAR) factors. The elliptical design storm methodology is summarized in section 7 but a more detailed description of the methodology can be found in Appendix C – Elliptical Frequency Storms in HEC-HMS.

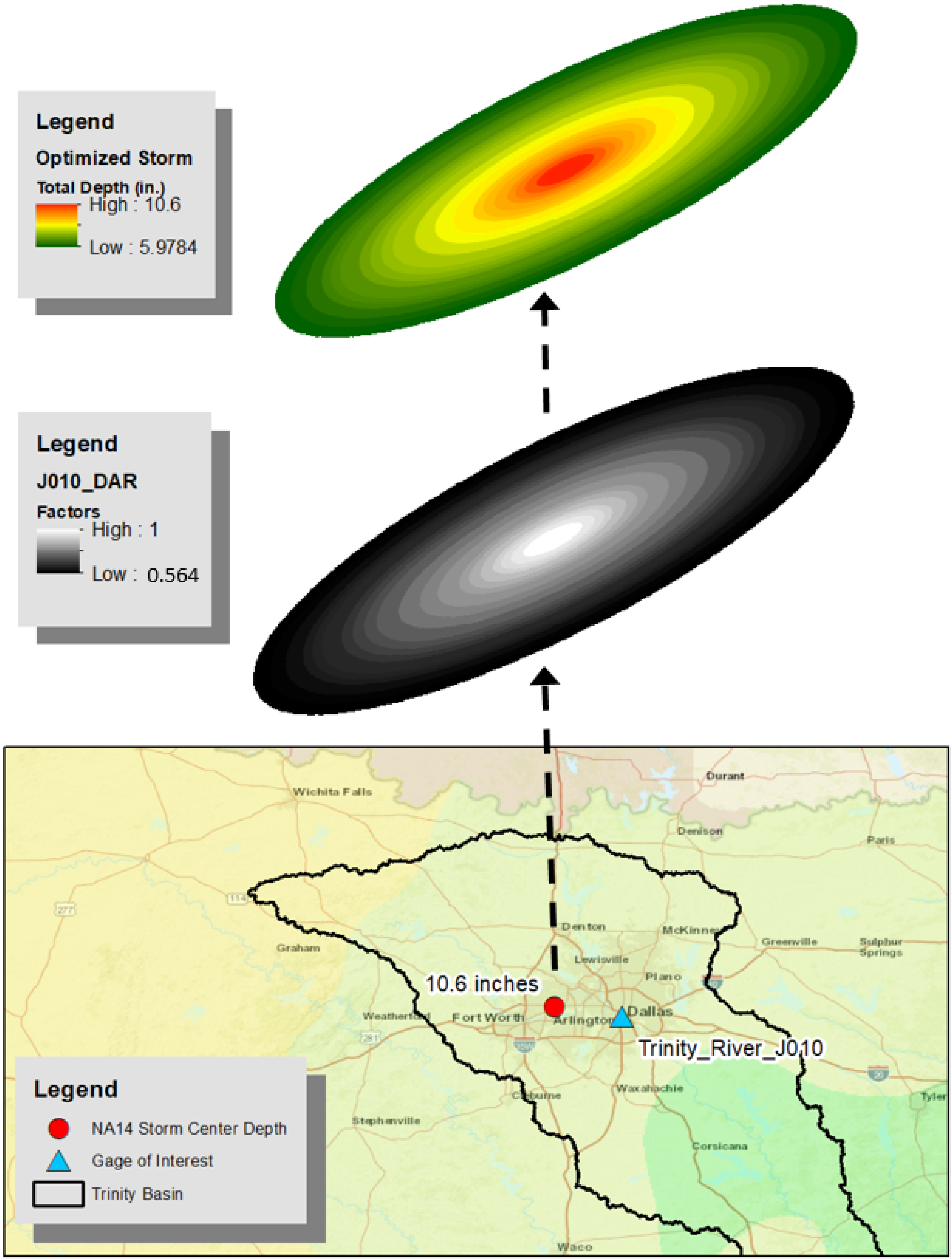


Figure 7.3: 100yr 48hr Elliptical Storm Generation - Upper Trinity Basin - Trinity River at Dallas

7.2.1 Elliptical Storm Area

This study uses a storm extent of 10,000 square miles. This is due to the historical rainfall studies rarely including data beyond 10,000 square miles (USACE, 1945). While this extent is somewhat arbitrary, testing was done to limit the storm extent to 3,000 square miles and the resulting peak discharges were slightly reduced. However the reduction in peak discharge was not significant because some of the rainfall beyond 3,000 square miles was falling outside the watershed and therefore not contributing to the runoff. Since there is no guidance or research on the subject, the storm extent of 10,000 square miles was used in this study.

7.2.2 Elliptical Storm Rainfall Depths

Elliptical storms were designed for each of the following annual exceedance probabilities (AEP): 1 in 2 years, 1 in 5 years, 1 in 10 years, 1 in 25 years, 1 in 50 years, 1 in 100 years, 1 in 200 years and 1 in 500 years. Point rainfall depths and durations were applied directly from NOAA Atlas 14 Volume 11 which contains depth duration frequency estimates of precipitation for Texas (NOAA, 2018). The point precipitation values that were applied to each elliptical storm were based on the storm center's location, not the location of the outlet of interest. For example, in Figure 7.3 above, the point precipitation values directly at the storm center (in red) were used to build the magnitude of the elliptical storm rather than the precipitation depths at the junction of interest (blue triangle).

7.2.3 Storm Ellipse Ratio

The HMR-52 study presents the option to design a storm with an ellipse ratio ranging from 2:1 to 3:1. For the Trinity basin, a 3:1 ellipse was used, as it better matched the long, narrow shape of the basin. A 2:1 ellipse was tested in several sections within the Trinity basin, and the optimized storm centerings, storm orientations, and resulting peak flows were generally similar to the results obtained from using a 3:1 ellipse.

7.2.4 Storm Temporal Pattern / Hyetograph

Historically, storms have varying intensities and temporal distributions and many studies have been done to document storm patterns. The six storm temporal distributions that were tested for a previous InFRM study on the Guadalupe Basin are shown in Figure 7.4. The Soil Conservation Service (1986) documented different distributions for the United States, and the Type II distribution was included in the testing. Other distributions were also tested, including the Frequency Rainfall Distributions from HEC-HMS with the storm centroid occurring at the 25%, 33%, 50%, 67% and 75% of the total distribution. The HEC-HMS Frequency Rainfall Distributions maintain the appropriate storm intensity throughout the storm. In other words, the 100 year, 1 hour rainfall is maintained with the 100 year, 3 hour rainfall and so on all the way through the 100 year, 48 hour rainfall.

While varying the temporal pattern distribution of the storm did have a small effect on the peak discharge, the difference was generally less than 5%. As with the Guadalupe study, the 50% storm distribution was also selected for the Trinity study due to its simplicity and maintaining the proper intensity throughout the storm period. This is also consistent with the temporal distribution used for the uniform rainfall method.

The magnitude of the Frequency Rainfall Distributions in HEC-HMS are created with point rainfall input. The relative magnitude of each 1-hr alternating block within our base temporal pattern was determined with the NOAA Atlas 14 point rainfall frequency data pertinent to the centroid of Tarrant County (1-hr, 2-hr, 3-hr, 6-hr, 12-hr, 24-hr, and 48-hr rainfall data for Tarrant County was used as input). Tarrant County was chosen to establish a base temporal pattern because it is part of the Dallas – Fort Worth metropolitan region which is the primary economic hub within the Trinity Basin. Furthermore, it is meteorologically similar to the majority of the Trinity Basin. As the storm is translated over the basin during the optimization process, the temporal pattern is scaled up or down from the base temporal pattern depending only on the NOAA Atlas 14 point rainfall data at the storm's current centering.

Testing on the Trinity River basin was done for shorter and longer design storm durations (24hr, 48hr, 96hr, and 240hr). In general, it was found that the longer storm durations produced slightly larger peak discharges due to small increases in volume being added at the beginning (and end) of the storm hyetograph. These small volume increases eat away at the initial losses causing more runoff when the intense, central portion of the storm arrives. For this study, the 48 hour storm duration was used throughout the watershed. This storm duration more closely coincides with the duration of the storm events used to calibrate the HMS model, and it also coincides with the storm duration used for the uniform rainfall HMS runs.

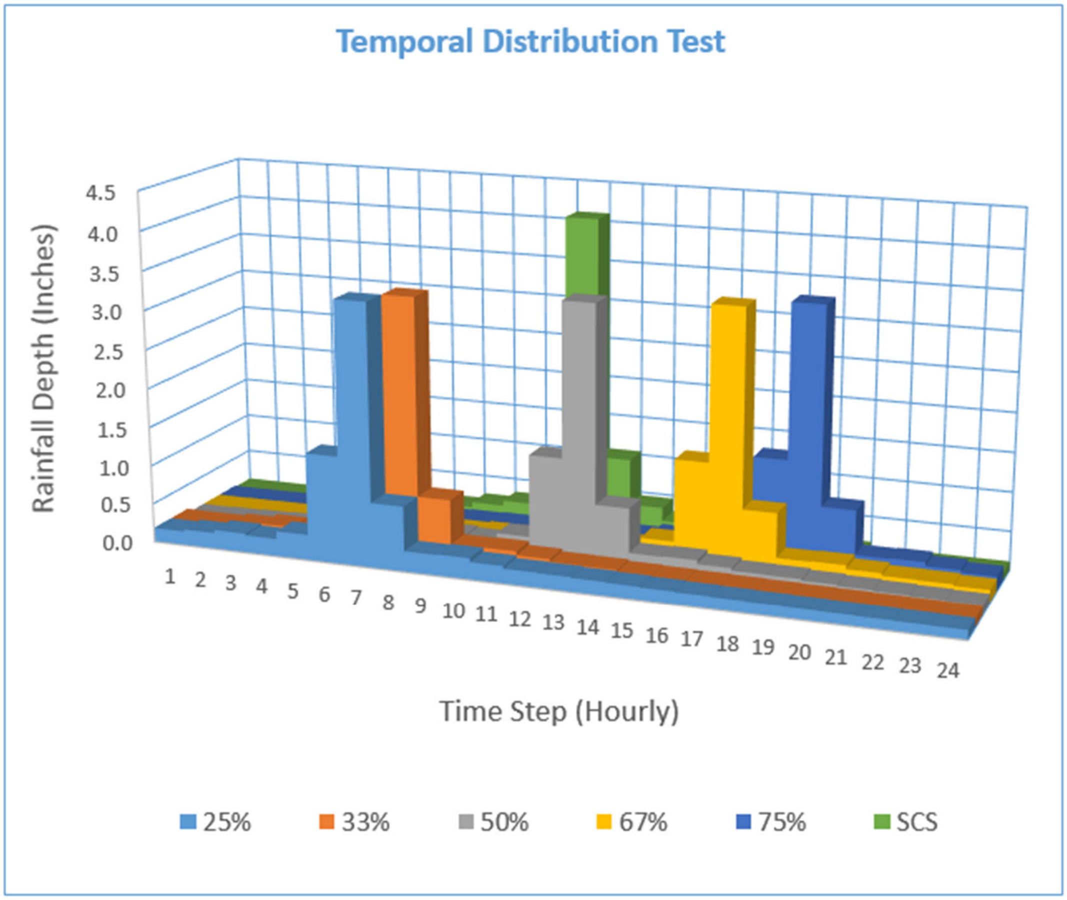


Figure 7.4: Tested Storm Temporal Distributions

7.2.5 Storm Depth Area Reduction Factors

The term depth area reduction factor refers to a storm that has been spatially normalized to a unit depth at the storm center. Thus the remainder of the storm is a percentage of the storm center. A depth area duration table is a way to track the volume of the storm. All storms have varying spatial and temporal patterns and this affects the depth area duration table of the storm.

For the elliptical frequency storms, the storm, shape, temporal pattern, duration, and rainfall depth at the center have all been accounted for. All that remains is to apply a depth area reduction curve to the storm to find the depths at each concentric ellipse. An example of a depth area reduction curve applied to an elliptical storm is shown in Figure 7.5.

A large amount of research and analysis went into the determination of the appropriate depth area reduction curve for this study. A previous study of elliptical storms had been done by USACE in 2012 for the Dallas Floodway

Extension project. This effort analyzed over 100 storms across Texas, Oklahoma, Arkansas and Louisiana. For this study, 35 historical storms more local to the Trinity watershed with total precipitation depths ranging from 5 to 11 inches were analyzed. In the end, a DAR curve for the Upper Trinity was implemented that roughly equated to the median of the 35 observed storms. The DAR curve used for the Lower Trinity is slightly different as it was created predominantly from tropical storm observations. Both curves are presented in Figure 7.6 and Table 7.1 below.

Rainfall Depth	Area of Ellipse	Depth Area Reduction Factor
10.0"	0 Sq. Mi.	100%
9.6"	10 Sq. Mi.	96%
9.2"	50 Sq. Mi.	92%
8.4"	100 Sq. Mi.	84%
7.5"	400 Sq. Mi.	75%
6.3"	800 Sq. Mi.	63%
5.0"	1,200 Sq. Mi.	50%

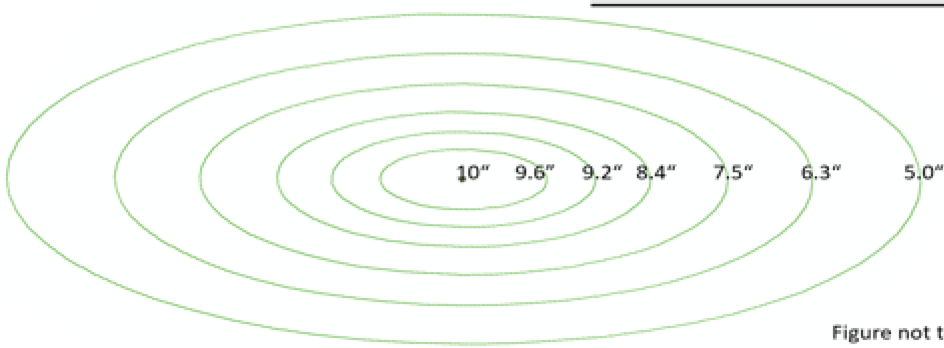


Figure not to scale. Only for demonstration.

Figure 7.5: Example of a Depth Area Reduction Curve Applied to an Elliptical Storm

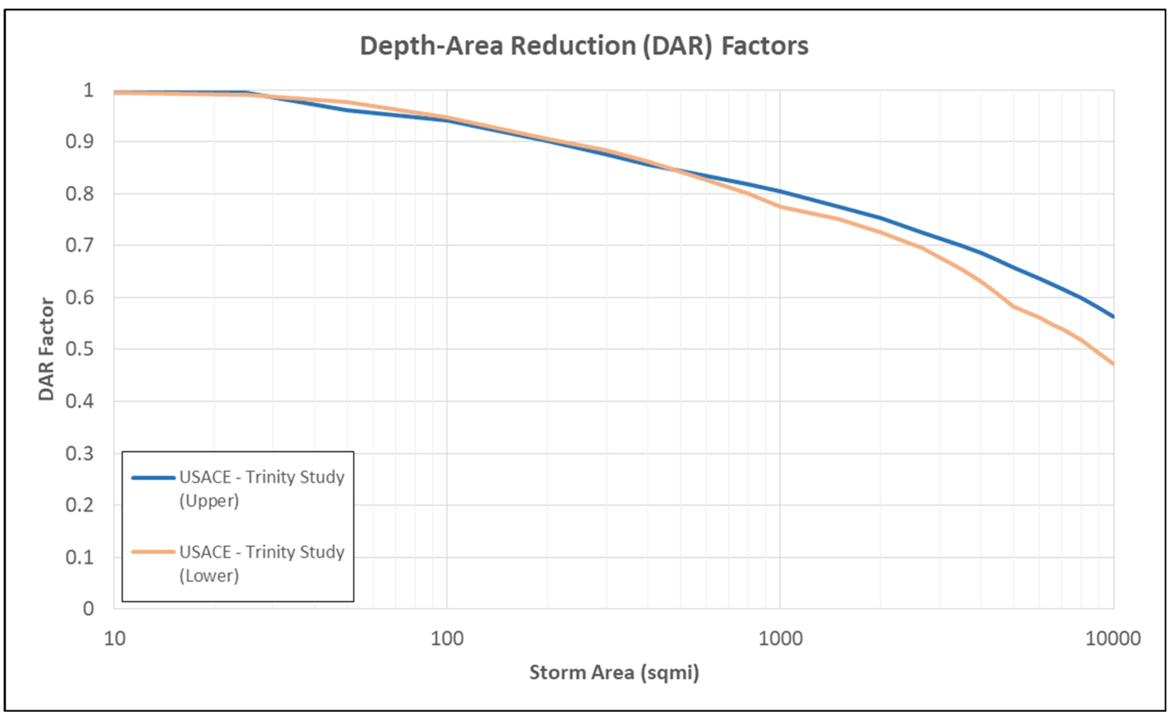


Figure 7.6: Adopted Depth Area Reduction Curves

Table 7.1: Adopted Depth Area Reduction Factors

Storm Area in Square Miles	DAR Factors – Trinity (Upper)	DAR Factors– Trinity (Lower)
1	1	1
10	1	1
25	0.997	0.991
50	0.96	0.976
100	0.94	0.946
200	0.902	0.906
300	0.875	0.884
400	0.855	0.862
600	0.834	0.827
800	0.818	0.801
1000	0.804	0.774
1500	0.775	0.75
2000	0.752	0.726
2667	0.726	0.695
3500	0.699	0.655
4000	0.685	0.631
4500	0.672	0.607
5000	0.658	0.583
6000	0.637	0.561
6500	0.626	0.55
7000	0.617	0.539
8000	0.599	0.517
9000	0.581	0.494
10000	0.564	0.472

7.2.6 Elliptical Storm Methodology - Lower Trinity Basin

The parameters listed above work well for the Upper Trinity Basin where the NOAA Atlas 14 precipitation gradient is, in general, spatially uniform and where the storms are largely convective. However, in the Lower Trinity Basin below the Trinity River near Crockett, TX USGS gage, the NOAA Atlas 14 precipitation gradient increases drastically as the basin approaches the Gulf of Mexico where tropical storms tend to drive larger precipitation events (Figure 7.7).

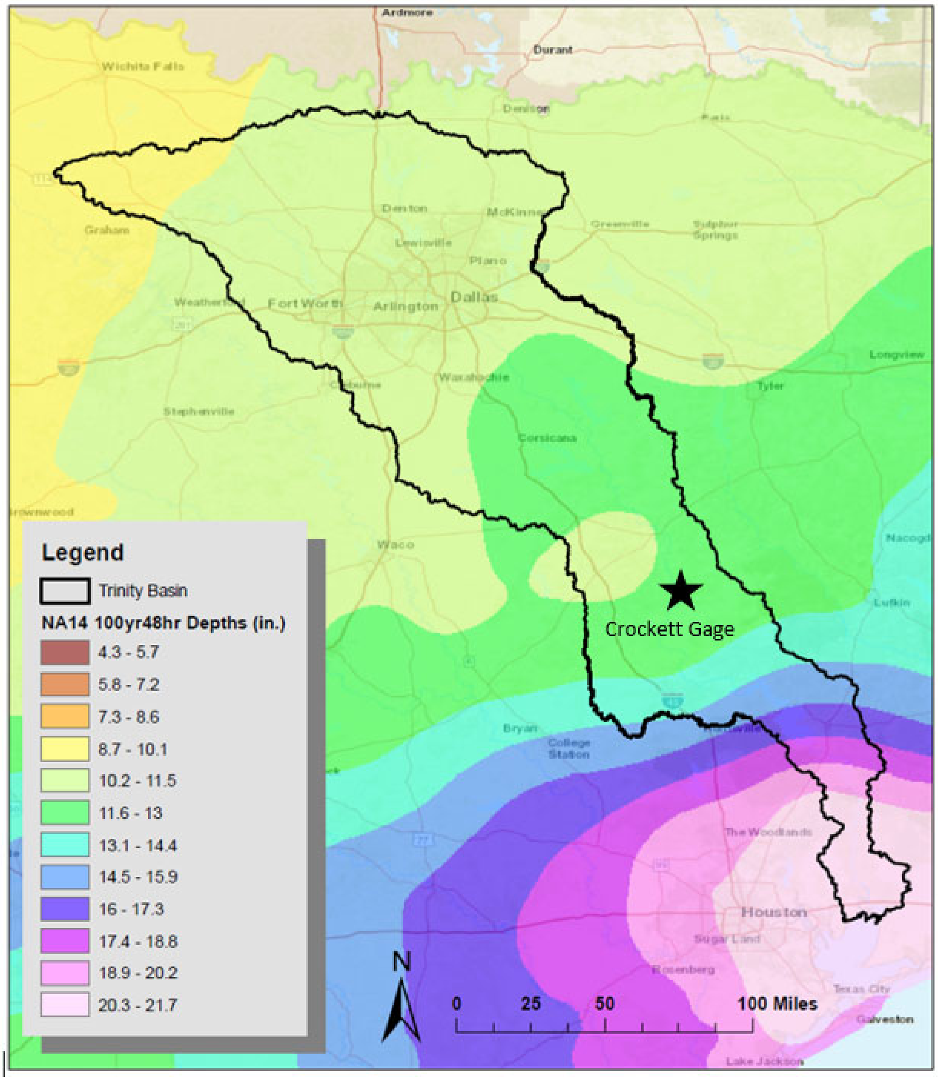


Figure 7.7: NOAA Atlas 14 100yr 48hr Precipitation Gradient - Trinity Basin

The main change in methodology that was employed in the Lower Trinity Basin involves how the NOAA Atlas 14 precipitation data and the DAR curve were used to create the elliptical storm. In the Upper Trinity, only one precipitation depth coinciding with the storm center was used to determine the volume of the storm at the innermost, center ellipse. The DAR curve was then applied to the queried storm center precipitation depth to determine the reduced volumes in the outer ellipses up to 10,000 sqmi (Figure 7.3 above). Due to the rapidly varying precipitation gradient near the Gulf, determining the outer elliptical volume based off of one center precipitation depth led to volume overestimation in latitudes above the storm center. These upper latitude regions of the storm were not being reduced enough. To compensate for this, a new methodology was applied in which all of the precipitation depths that fell under the 10,000 sqmi elliptical storm positioning were queried instead of just the one depth at the storm center. Then all of the queried precipitation depths were reduced based off of which of the concentric, DAR ellipses they overlapped with (Figure 7.8 below). In regions where the precipitation depths vary greatly over a short distance, this method performs better since the precipitation gradient is reflected in the makeup of the elliptical storm.

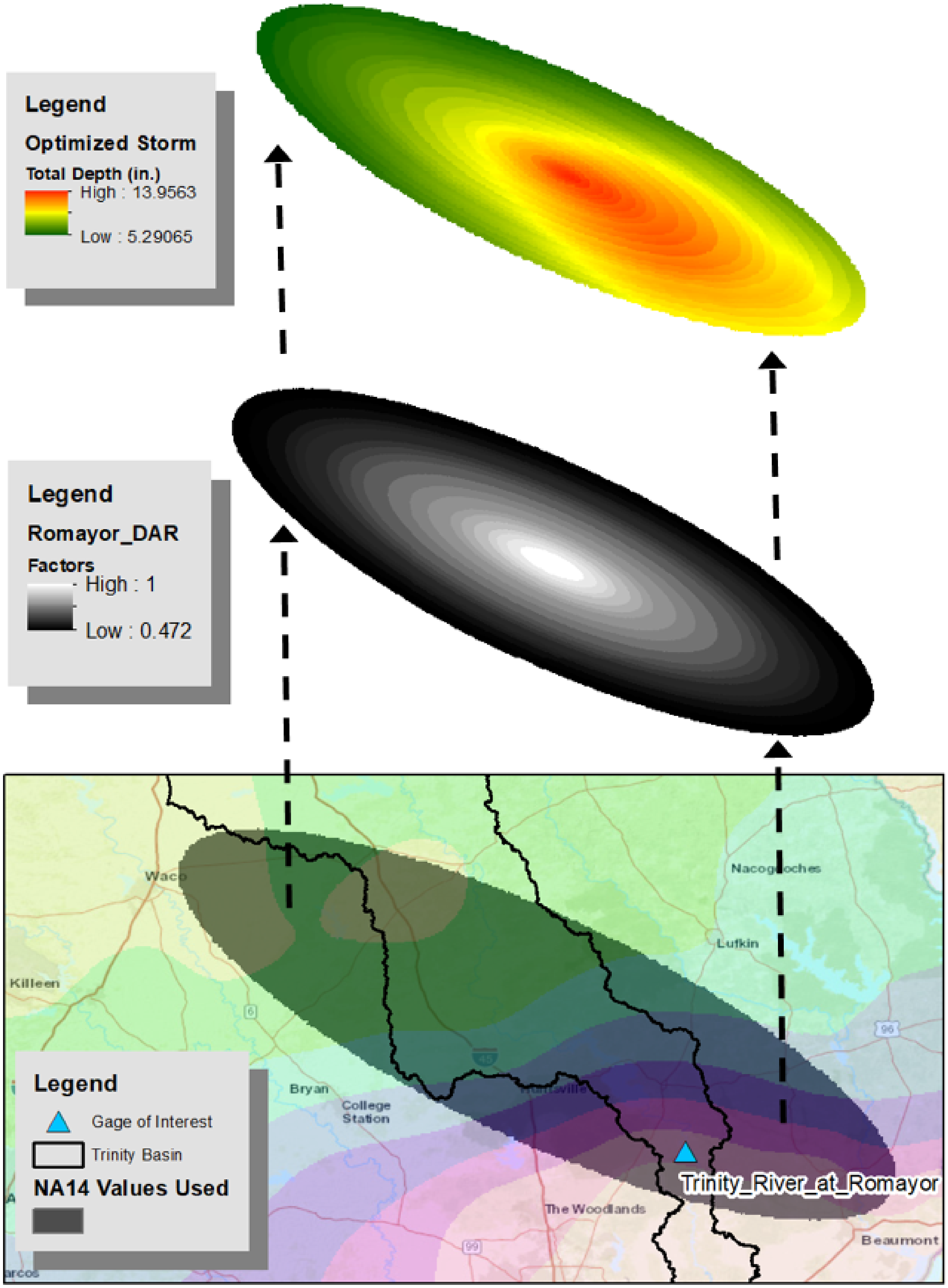


Figure 7.8: 100yr 48hr Elliptical Storm Generation - Lower Trinity Basin - Trinity River at Romayor

A second, small deviation from the prior methodology involved changing the temporal pattern parameter. For the Upper Trinity Basin, a base temporal pattern derived from precipitation depth input specific to Tarrant County was used. For the Lower Trinity Basin, an improvement was made in the methodology that better accounts for potential differences in meteorology. Instead of manipulating a base temporal pattern, a customized temporal pattern unique to each storm centering was built. At each storm centering, the 1-hr, 2-hr, 3-hr, 6-hr, 12-hr, 24-hr, and 48-hr duration precipitation depths were queried and the alternating block method was applied to create a temporal pattern.

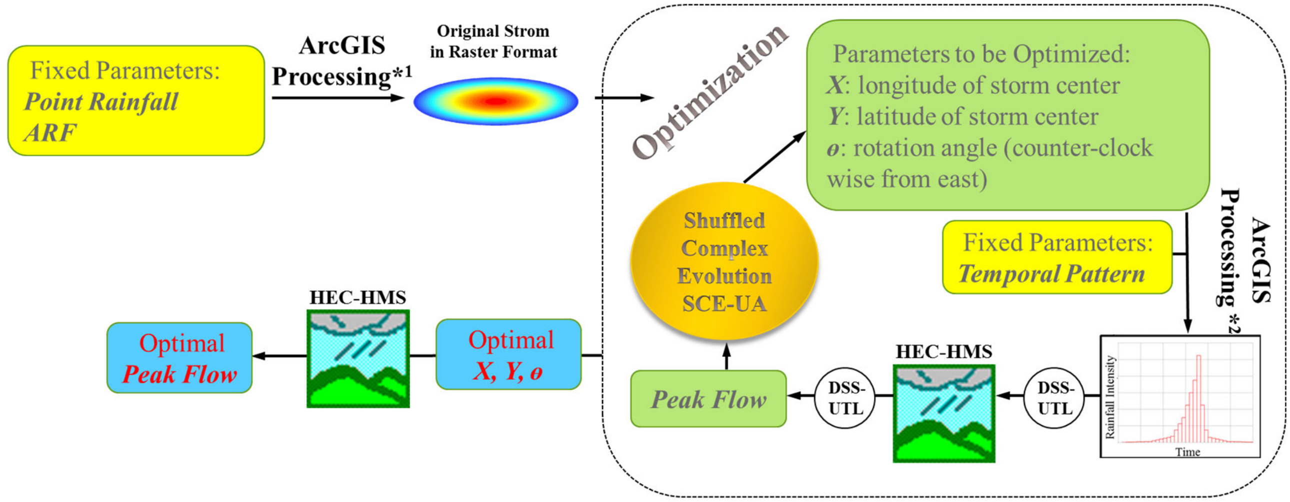
A third and final change involved the DAR curve that was used for the Lower Trinity Basin. A smaller, subset of observed storms that occurred in the Lower Trinity Basin were analyzed in an effort to better account for the potential meteorological differences near the Gulf. In the end, a slightly different DAR curve was adopted for this region (Lower) of the Trinity basin. Both the Upper and Lower Trinity Curves are shown in Figure 7.6.

7.3 OPTIMIZATION OF THE STORM CENTER LOCATION

For this study, a script was developed for the InFRM team that automatically locates optimal centering locations (x and y) and rotations (ϴ) of (spatially varied) elliptical frequency storms for a list of receiving junctions in a watershed. The script was expected to obtain the combination of the three parameters (x, y, and ϴ) that maximized peak flow at desired junctions while achieving the following objectives:

- To complete the task efficiently.
- To allow users to customize the scripts easily based on their needs.
- To generate reasonable results that can be validated manually.
- To outperform the manual grid search method in terms of precision, accuracy and efficiency.
- To function normally on any machine at USACE with the available software and hardware.

Figure 7.9 illustrates the schematic flow of the storm optimization. The scheme begins with creating a spatially varied design storm in raster format using ArcGIS. Given the point rainfall (total rainfall at the storm centroid) and the areal reduction factor (ARF), a peak hour storm raster is digitized by creating a series of concentric ellipses and then converting them to raster format. An optimization stage is followed including two major components: 1) parameter update/optimization and 2) automatic simulation of the HEC-HMS hydrologic model. In each iteration of the optimization process, the peak hour storm raster is first shifted and rotated due to updated parameters (x, y, and ϴ); and then allocated into each subbasin as mean areal precipitation (MAP). Since the MAP value for each subbasin only represents the amount of rain during the peak hour (hour 25 of a 48 hour storm), the remaining 47 values are ratioed to create a time series. The time series MAP values, i.e. the hyetographs, are stored in DSS format and transmitted to the HMS model for simulations. After each simulation, the corresponding peak flow value at a desired junction is extracted from the output DSS file. Based on the extracted peak flow value, an optimization algorithm will update the parameters (x, y and ϴ) and then optimization proceeds into the next iteration. After all optimization iterations for a junction are complete, an optimized storm center (x and y) and orientation (ϴ) that leads to a maximum peak flow at a given junction being determined. The optimization process can then be repeated for the next junction of interest.



*1. involves creating ellipse polygons and converting polygon to raster.
*2. involves shifting raster, rotating raster and calculating zonal statistics (for MAP).

Figure 7.9: Schematic Flowchart for the Storm Optimization Script

Originally, the scripts were designed to automate a grid search, where all possible combinations of parameters (i.e. the 'grids') are exhaustively tested and the optimal combination of the three parameters (x, y, and ө) can then be obtained. Although the approach of grid search seems straightforward, it does suffer from high computational cost because the computational run time depends on the number of grids, which is further constrained by the range and the interval of each parameter. Given the need of maintaining a certain level of precision or keeping constant intervals of the parameters, the University of Texas at Arlington (UTA) team found that the grid search approach might not be appropriate for this project since the computational run time was excessively lengthy – it increases exponentially with greater drainage area (more possible x and y values).

In order to overcome this issue, the UTA team selected a global optimization (GO) algorithm entitled shuffled complex evolution (SCE) (Duan et al., 1993) - a random sampling approach. Instead of exhausting all possible grids, the random sampling approach tests the objective function around some sampled grids in an iteration while learning about the structure of the objective function for improving the sampling of grids in the next iteration. More details about GO and SCE are included in Appendix C – Elliptical Frequency Storms in HEC-HMS.

7.4 ELLIPTICAL FREQUENCY STORM LOCATIONS

The final optimized storm center locations (x, y) and rotations (ө) for every node of interest in the Trinity watershed can be found in Appendix C – Elliptical Frequency Storms in HEC-HMS. Rotation angles are measured counter-clockwise from the positive x-axis. These location and rotation parameters were determined from 100yr frequency optimizations, and are assumed to be the same for all other frequency events (2yr – 500yr). Testing showed that, in general, optimized locations and orientations did not significantly change between frequency events. Once the optimum storm center location and rotation were determined for each location of interest, the elliptical frequency storms for the standard eight frequency events were constructed using the appropriate NOAA Atlas 14 point rainfall depths.

7.5 ELLIPTICAL FREQUENCY STORM LOSS RATES

The elliptical frequency storms were then applied to the final HEC-HMS basin model with the same frequency loss rates that were used for the uniform rainfall method (Section 6). In some cases, the 2-yr through 10-yr losses had to be re-adjusted in order to maintain consistency with the frequent end of the statistical frequency curves at the USGS gages. This final adjustment was performed because of the increased level of confidence in the statistical frequency curve for the 2 through 10-yr recurrence intervals. The complete list of frequency losses are included in Appendix C – Elliptical Frequency Storms in HEC-HMS.

7.6 ELLIPTICAL FREQUENCY STORM RESULTS FROM HEC-HMS

The frequency peak flow values were then calculated in HEC-HMS by applying the appropriate, optimized elliptical frequency storms for each junction of interest in the final HEC-HMS basin model. These results will later be compared to the uniform rain results from HEC-HMS along with other methods from this study.

Figure 7.10 and Figure 7.12 are examples of the 100yr 48hr heatmap results for the optimization of each junction of interest in the Elliptical Storm HMS model. For each junction of interest, the optimization script ran 300+ times recording the junction flow rate for various storm centerings and orientations. Each of the recorded storm centerings (x,y) and resulting flow rates (z) at the junction of interest were recorded and used to create a rasterized heat map. The red shading represents storm locations that led to relatively high flow rates at the junction whereas the green shading represents storm locations that led to relatively low flow rates.

Figure 7.11 and Figure 7.13 are examples of the final, total storm depths and optimized storm configurations for each junction. Note that the peak flow values recorded in the "Heat Map" figures may differ slightly from the final peak flow values recorded in the final "Elliptical Storm" figures and in Table 7.2. This is due to small tweaks to the HEC-HMS model parameters that were done after the 100yr48hr storm centerings were determined.

The complete set of heat map and final storm maps can be found in Appendix C – Elliptical Frequency Storms in HEC-HMS.

The elliptical design storm results for all of the analyzed junctions are included in Table 7.2. In some cases, one may observe that the simulated peak discharge decreases in the downstream direction. It is not an uncommon phenomenon to see decreasing frequency peak discharges for some river reaches as flood waters spread out into the floodplain and the hydrograph becomes dampened as it moves downstream. This can be due to a combination of peak attenuation due to river routing as well as the difference in timing between the peak of the main stem river versus the runoff from the local tributaries and subbasins.

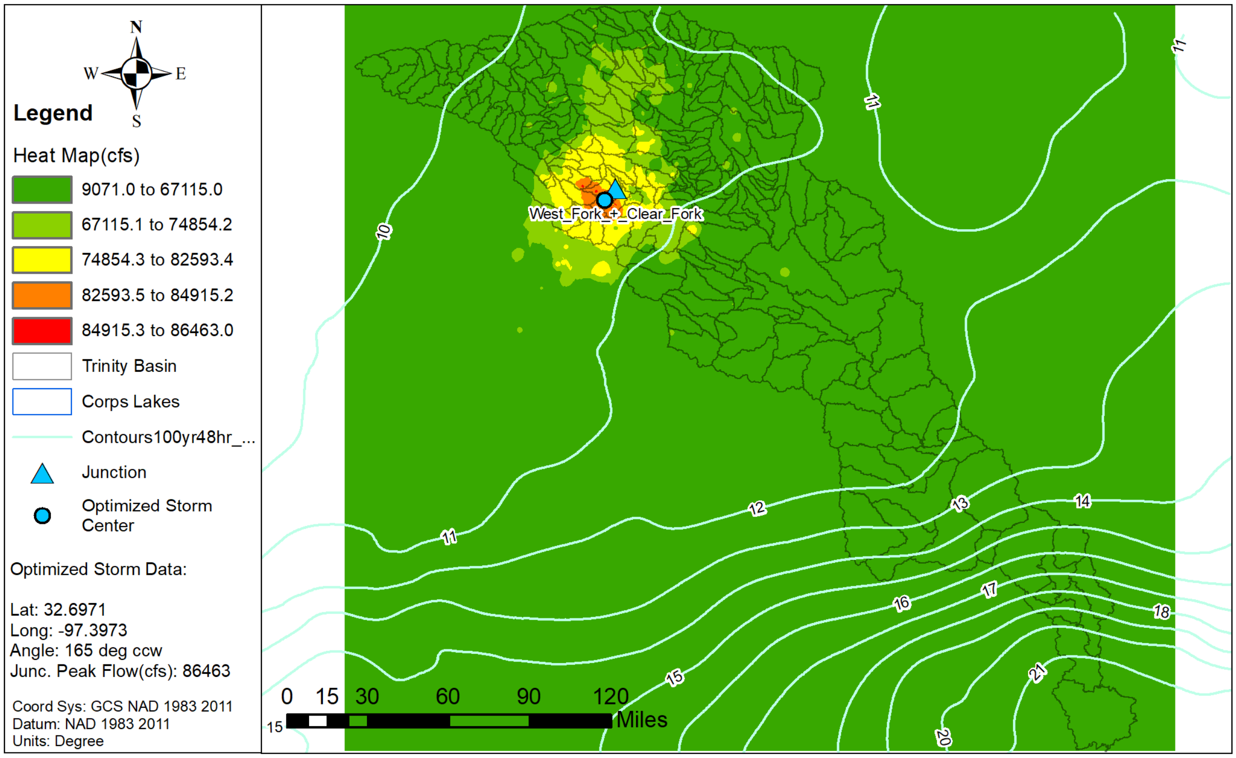


Figure 7.10: Elliptical Storm Heat Map for the West Fork Trinity River below Clear Fork

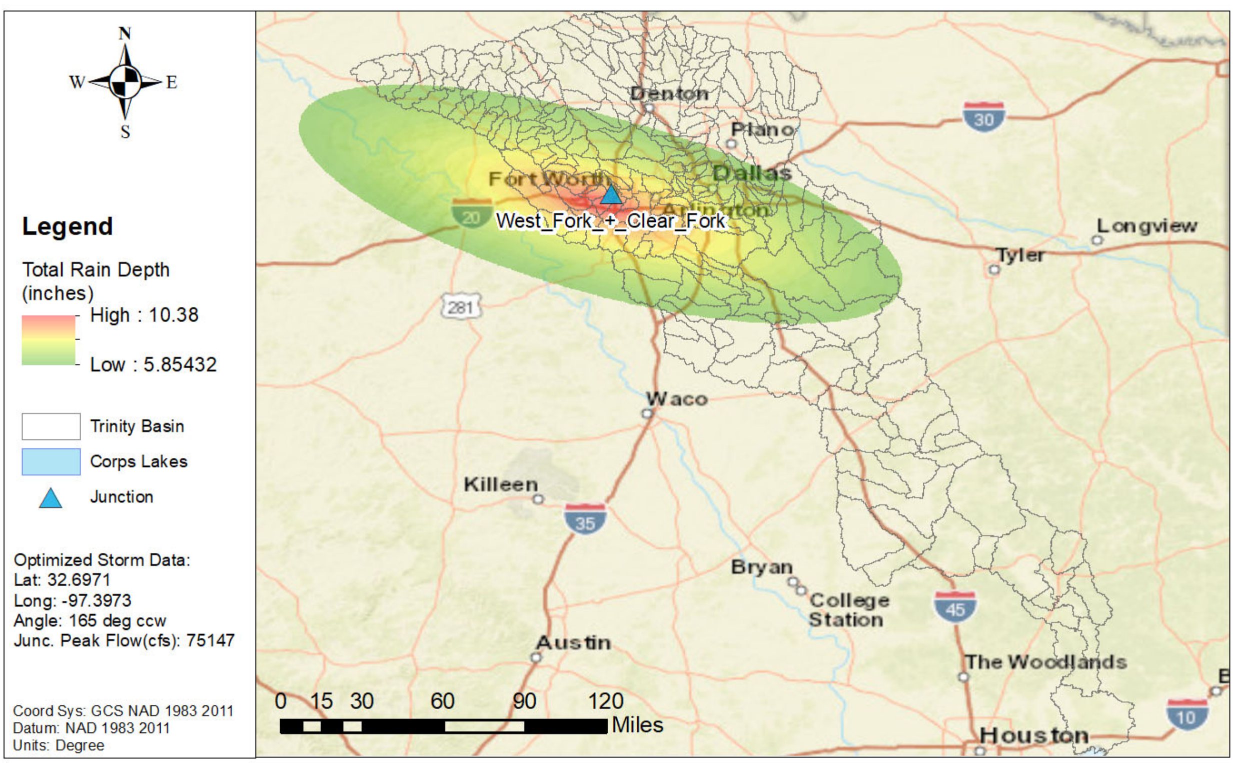


Figure 7.11: 100yr Elliptical Storm for the West Fork Trinity River below the Clear Fork

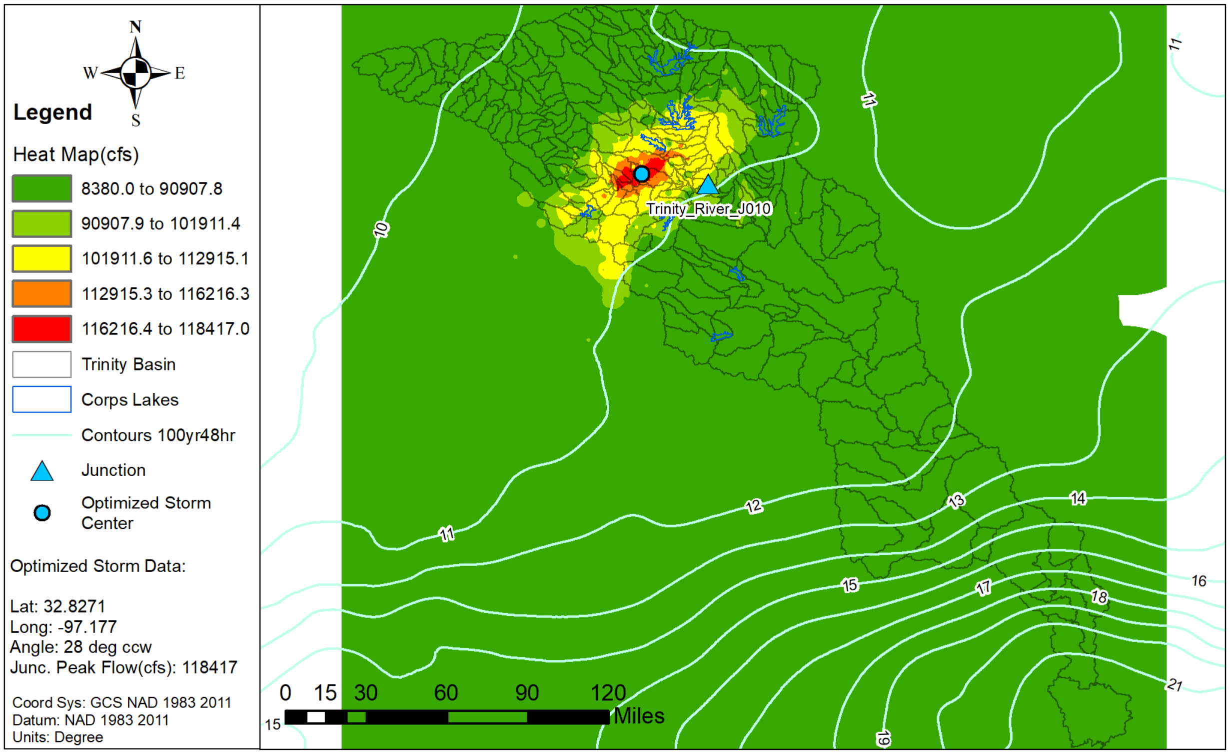


Figure 7.12: Elliptical Storm Heat Map for the Trinity River at Dallas Gage

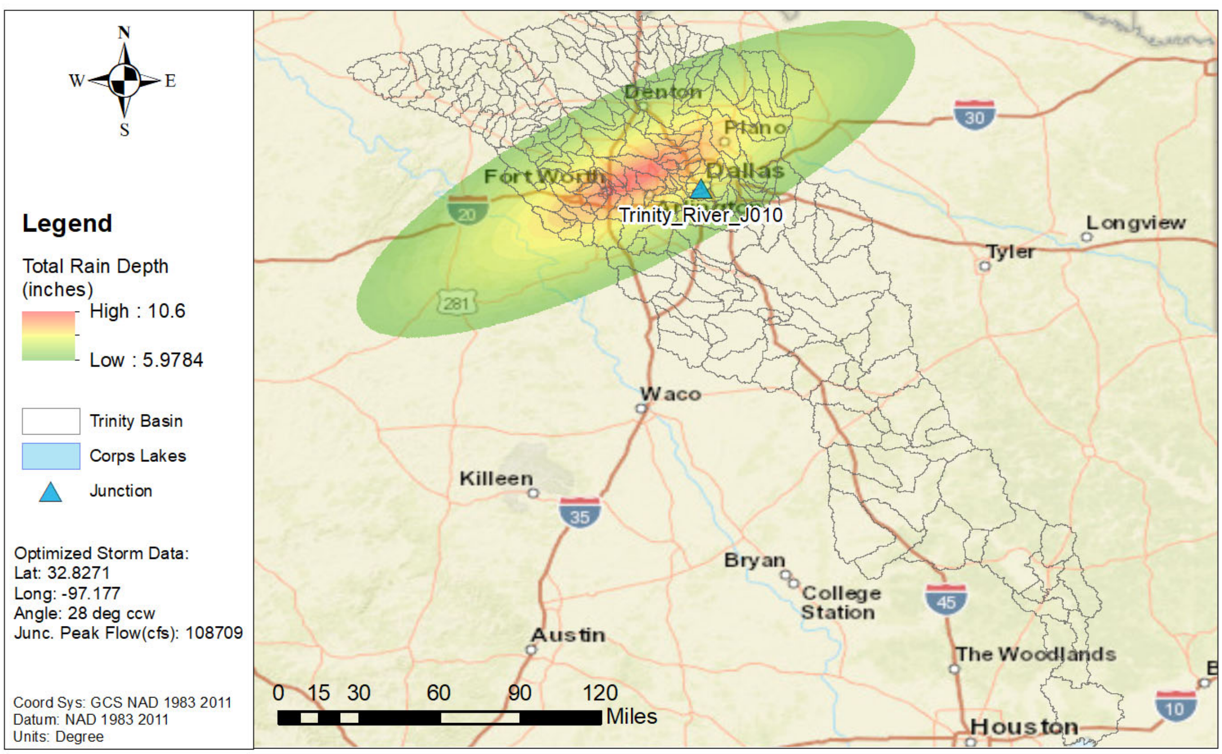


Figure 7.13: 100yr Elliptical Storm for the Trinity River at Dalls Gage

Table 7.2: Summary of Discharges (cfs) from the HEC-HMS Elliptical Frequency Storm Method

Location Description	HEC-HMS Element Name	Drainage Area*	50%	20%	10%	4%	2%	1%	0.50%	0.20%
		sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR
West Fork Trinity River above Turkey Creek	West_Fork_abv_TurkeyCk	403.1	2,000	7,200	13,300	22,500	32,700	47,800	62,500	83,300
West Fork Trinity River below Turkey Creek	West_Fork_J050	439.2	2,100	7,500	13,800	23,300	34,100	50,000	65,400	88,000
West Fork Trinity River above Big Cleveland Creek	WestFork_abv_Big_Cleveland	549.4	1,900	6,200	11,100	18,500	27,200	41,300	55,800	76,800
West Fork Trinity River below Big Cleveland Creek	West_Fork_J070	648.1	2,800	6,200	11,100	18,600	27,500	42,800	59,200	83,100
West Fork Trinity River near Jacksboro, TX USGS gage	West_Fork_J080	668.7	1,900	5,900	10,600	17,800	26,300	40,700	56,200	79,500
West Fork Trinity River below Lost Creek	West Fork + Lost Ck	711.2	2,000	6,100	11,000	18,600	27,300	41,800	57,500	81,700
West Fork Trinity River above Carroll Creek	West_Fork_abv_CarrollCk	750.8	1,900	5,900	10,700	18,300	26,800	41,000	56,500	80,100
West Fork Trinity River below Carroll Creek	West_Fork_J090	792.1	2,100	9,500	20,500	29,000	36,600	45,800	54,500	69,700
West Fork Trinity River above Beans Creek	WestFork_abv_Beans_Ck	827.7	1,900	10,000	22,100	31,700	40,400	51,100	61,100	78,000
West Fork Trinity River below Beans Creek	West Fork + Beans Ck	874.6	1,700	11,600	26,900	38,900	49,700	62,900	74,300	93,300
Bridgeport Reservoir Inflow	Bridgeport Inflow	1095.7	3,700	24,500	58,400	83,000	105,500	132,300	157,200	192,200
Bridgeport Reservoir Outflow	Bridgeport Reservoir	1095.7	2,600	5,400	11,600	12,400	13,200	21,100	29,300	39,000
West Fork Trinity River above Dry Creek	West_Fork_abv_DryCk	1136.2	2,200	5,500	11,500	12,400	13,300	21,100	29,500	39,200
West Fork Trinity River below Dry Creek	West_Fork_J100	1162.9	1,800	5,900	12,600	17,500	21,800	26,700	31,400	37,800
West Fork Trinity River above Big Sandy Creek	WestFork_abv_Big_Sandy_Ck	1169.5	1,800	5,300	11,800	17,200	22,300	27,600	32,500	39,200
Big Sandy Creek nr Bridgeport USGS Gage at Hwy 114 bridge	Big_Sandy_Ck_J030	334.3	3,600	7,900	12,300	18,800	26,200	36,600	47,000	64,600

Location Description	HEC-HMS Element Name	Drainage Area*	50%	20%	10%	4%	2%	1%	0.50%	0.20%
		sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR
Big Sandy Creek above the West Fork Trinity River	Big_Sandy_Ck_abv_WestFork	353.9	3,500	7,900	11,900	18,900	26,400	36,700	47,300	64,500
West Fork Trinity River below Big Sandy Creek	West Fork + Big Sandy Ck	1523.5	4,400	11,200	19,700	28,200	36,600	49,000	61,100	78,400
West Fork Trinity River at FM 3259 near Paradise, TX	West_Fork_J110	1551.8	4,200	10,500	17,500	26,600	36,400	49,300	61,800	80,000
West Fork Trinity River above Salt Creek	WestFork_abv_Salt_Ck	1573.7	3,600	9,700	15,300	22,800	31,700	44,500	56,600	74,800
West Fork Trinity River below Salt Creek	West Fork + Salt Ck	1680.4	3,300	9,400	17,000	27,000	38,600	55,600	71,700	95,600
West Fork Trinity River near Boyd, TX - USGS Gage at FM 730 bridge	West_Fork_J120	1710.8	3,000	9,300	16,800	26,700	38,200	54,700	71,500	96,400
West Fork Trinity River about 0.8 miles upstream of FM 4757 in Wise County	West_Fork_J130	1751.9	3,200	9,800	16,700	26,300	37,400	53,300	69,000	92,900
Eagle Mountain Reservoir Inflow	Eagle Mountain Inflow	1956.6	9,300	28,800	43,300	66,800	83,600	102,700	120,300	143,600
Eagle Mountain Reservoir Outflow	Eagle Mountain Reservoir	1956.6	3,800	7,300	13,800	17,200	21,500	27,100	33,000	42,500
Lake Worth Inflow	Lake Worth Inflow	2050.8	4,800	11,800	16,500	25,400	31,200	37,800	43,500	51,500
Lake Worth Outflow	Lake Worth	2050.8	3,000	7,300	13,900	17,400	21,600	27,400	33,400	42,800
West Fork Trinity River above the Clear Fork	WestFork_abv_Clear_Fork	2078.7	3,200	8,200	11,700	18,200	21,300	25,000	29,700	36,100
Benbrook Lake Inflow	Benbrook Inflow	429.2	24,900	47,500	61,800	79,500	94,800	111,900	128,800	154,600
Clear Fork above Marys Creek	Clear_Fork_abv_Marys_Ck	9.4	3,200	4,900	5,900	7,300	8,500	9,700	10,900	12,800
Clear Fork below Marys Creek	Clear Fork + Marys Creek	63.6	5,200	14,800	25,800	39,500	47,400	56,700	68,300	79,800
Clear Fork Trinity River at Fort Worth USGS gage	Clear_Fork_J020	89.0	7,600	18,200	29,100	46,900	55,100	64,000	73,000	82,300
Clear Fork Trinity River above the West Fork	Clear_Fork_abv_WestFork	93.9	8,100	19,200	30,600	45,300	53,300	62,100	71,000	80,900
West Fork Trinity River below the Clear Fork (West Fork at Fort Worth USGS gage)	West Fork + Clear Fork	2172.5	10,700	23,600	36,600	54,300	64,300	75,200	86,400	100,000

Location Description	HEC-HMS Element Name	Drainage Area*	50%	20%	10%	4%	2%	1%	0.50%	0.20%
		sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR
West Fork Trinity River above Marine Creek	WestFork_abv_MarineCk	2173.7	10,700	24,000	36,900	53,500	63,400	73,700	86,500	100,200
West Fork Trinity River below Marine Creek	West Fork + Marine Ck	2195.4	11,000	24,700	37,900	54,900	65,200	76,000	89,000	103,300
West Fork Trinity River above Sycamore Creek	West_Fork_J140	2204.6	11,300	24,000	37,800	53,900	62,600	73,700	88,000	104,400
West Fork Trinity River below Sycamore Creek (West Fork Trinity River at Beach Street USGS Gage)	West_Fork_J150	2243.8	11,500	23,700	36,900	56,100	66,700	77,200	90,400	108,400
West Fork above Big Fossil	WestFork_abv_BigFossil	2256.8	10,200	21,400	34,600	53,200	64,400	76,000	89,000	107,100
West Fork Trinity River and Big Fossil Creek Confluence	West_Fork_J160	2333.4	12,300	23,700	38,000	60,600	76,400	92,700	108,500	130,200
West Fork Trinity River below Village Creek	West Fork + Village Ck	2554.0	11,700	21,100	36,400	55,000	70,200	89,200	108,600	138,800
West Fork Trinity River below Johnson Creek	West_Fork_J170	2618.6	8,600	17,200	27,000	44,000	58,300	78,100	96,800	129,200
West Fork Trinity River at Grand Prairie USGS gage	West_Fork_J180	2623.4	8,500	17,200	27,100	44,200	58,400	78,000	96,500	128,100
West Fork Trinity River above Big Bear Creek	West_Fork_abv_Big_Bear_Ck	2625.5	8,400	16,500	26,400	42,600	56,700	73,200	93,000	124,500
West Fork Trinity River below Big Bear Creek	West Fork + Bear Ck	2718.8	10,000	17,600	29,700	50,000	66,800	85,300	107,200	143,000
West Fork Trinity River above Mountain Creek	West_Fork_abv_Mountain_Ck	2727.4	10,000	17,500	29,100	46,200	62,600	81,600	101,600	134,400
West Fork Trinity River below Mountain Creek	West Fork + Mountain Ck	2807.6	14,100	22,900	30,300	47,300	63,900	82,900	103,100	137,000
West Fork Trinity River above the Elm Fork Trinity River	West_Fork_abv_Elm_Fork	2820.9	13,100	21,700	29,900	46,800	63,600	83,000	103,100	136,100
Ray Roberts Lake Inflow	Ray Roberts Inflow	692.6	59,500	95,900	120,600	153,100	182,400	216,100	249,700	296,000
Elm Fork Trinity River above Clear Creek	Elm_Fork_abv_Clear_Ck	36.9	2,500	5,400	8,300	11,000	13,200	15,900	18,300	21,700

Location Description	HEC-HMS Element Name	Drainage Area*	50%	20%	10%	4%	2%	1%	0.50%	0.20%
		sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR
Elm Fork Trinity River below Clear Creek	Elm Fork + Clear Ck	388.1	8,500	14,000	20,000	28,300	41,700	59,900	77,500	100,300
Lewisville Lake Inflow	Lewisville Inflow	968.2	42,500	69,000	88,200	112,500	135,100	159,700	182,700	215,000
Elm Fork Trinity River above Indian Creek	Elm_Fork_abv_Indian_Ck	21.4	1,600	3,200	4,400	6,500	7,700	9,100	10,400	12,200
Elm Fort Trinity River below Indian Creek	Elm Fork + Indian Ck	37.5	3,600	6,800	9,100	13,200	15,500	18,100	20,600	24,200
Elm Fork Trinity River below Timber Creek	Elm Fork + Timber Ck	61.5	4,200	7,700	9,800	14,000	16,600	20,200	23,600	28,200
Elm Fork Trinity River above Denton Creek	Elm_Fork_abv_Denton_Ck	79.9	5,800	10,400	13,300	18,700	22,200	26,700	31,000	36,900
Denton Creek nr Justin, TX USGS gage	Denton_Ck_J030	400.0	4,500	11,300	17,400	26,000	35,700	46,800	62,700	82,600
Denton Creek below Oliver Creek	Denton_Ck_J040	475.3	9,400	18,900	26,500	36,000	45,200	55,300	64,500	77,600
Denton Creek above Elizabeth Creek	Denton_Ck_abv_Elizabeth_Ck	506.1	9,800	18,600	25,800	35,600	45,800	57,100	69,500	85,200
Denton Creek below Elizaveth Creek	Denton_Ck_J050	599.7	15,800	29,300	39,500	53,400	68,400	85,300	102,000	123,900
Grapevine Lake Inflow	Grapevine_Inflow	694.4	16,000	28,200	38,600	52,200	66,900	84,800	101,600	124,500
Denton Creek above the Elm Fork Trinity River	Denton_Ck_abv_Elm_Fork	24.3	2,300	4,300	5,800	8,800	10,400	12,200	14,000	16,300
Elm Fork Trinity River near Carrollton USGS gage	Elm Fork + Denton Ck	104.2	7,500	13,400	17,700	25,600	30,100	35,600	41,500	49,300
Elm Fork Trinity River at Interstate 635	Elm_Fork_J060	143.4	12,300	17,500	21,400	29,300	34,900	41,300	47,400	56,400
Elm Fork Trinity River above Hackleberry Creek	Elm_Fork_abv_Hackberry_Ck	143.4	8,900	14,700	19,200	28,000	33,700	40,200	46,600	54,800
Elm Fk Trinity Rv at Spur 348 in Irving; TX USGS gage	Elm_Fork_J070	180.4	10,800	15,400	20,000	28,800	35,000	42,400	49,400	59,100
Elm Fork Trinity River above Bachman Branch	Elm_Fork_abv_Bachman_Branch	202.6	10,000	14,400	18,700	26,100	32,000	39,500	45,900	54,700

Location Description	HEC-HMS Element Name	Drainage Area*	50%	20%	10%	4%	2%	1%	0.50%	0.20%
		sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR
Elm Fork Trinity River below Bachman Branch (at Frasier Dam USGS gage)	Elm Fork + Bachman Branch	216.7	10,700	15,000	19,100	26,600	32,700	40,400	46,900	55,900
Elm Fork Trinity River above the West Fork Trinity River	Elm_Fork_abv_West_Fork	222.8	8,800	14,600	19,000	25,900	32,000	40,000	46,400	55,700
Trinity River below the West Fork and Elm Fork confluence	West Fork + Elm Fork	3043.7	19,300	31,100	41,900	67,100	89,600	113,800	140,200	182,800
Trinity River at Dallas, TX USGS gage	Trinity_River_J010	3056.1	19,000	31,000	42,100	66,200	88,500	113,100	138,900	181,500
Trinity River at the Corinth Street bridge in Dallas, TX	Trinity_River_J020	3099.0	19,000	31,000	42,200	66,300	88,500	113,500	139,100	182,300
Trinity River below White Rock Creek	Trinity River + White Rock	3233.9	21,800	35,500	48,000	68,200	90,000	116,800	143,700	185,500
Trinity River below Honey Springs Branch (Trinity River below Dallas, TX USGS gage)	Trinity_Rv + Honey_Springs	3256.5	21,900	35,700	48,300	68,400	90,000	116,700	143,800	185,700
Trinity River below Five Mile Ceek	Trinity_River + Five_Mile_Ck	3328.8	21,100	34,600	47,300	67,600	88,000	114,100	140,200	180,300
Trinity River above Ten Mile Creek	Trinity_River_abv_Tenmile_Ck	3367.7	20,100	29,900	40,700	59,400	78,800	104,000	125,700	161,300
Trinity River below Ten Mile Creek	Trinity River + Tenmile Ck	3469.8	20,200	30,800	40,600	59,300	78,500	103,700	124,800	160,400
Trinity River above the East Fork Trinity River	Trinity_River_abv_East_Fork	3529.4	19,500	28,400	37,700	56,700	74,900	99,500	122,800	156,000
Lavon Lake Inflow	Lavon Inflow	768.2	24,100	42,300	53,600	69,400	79,900	90,700	106,400	128,700
Ray Hubbard Lake Inflow	Ray Hubbard Inflow	301.8	31,100	50,600	62,300	78,800	90,500	103,200	119,000	141,400
East Fork Trinity River near Forney USGS gage	East_Fork_nr_Forney	349.9	14,000	25,700	35,100	47,200	55,900	65,900	89,500	113,800
East Fork Trinity River above Buffalo Creek	East_Fork_abv_Buffalo_Ck	359.5	12,300	23,200	29,700	44,300	53,700	63,800	85,100	111,700
East Fork Trinity River below Buffalo Creek	East_Fork + Buffalo_Ck	393.9	13,000	24,500	31,700	47,000	56,900	67,900	90,600	119,000
East Fork Trinity River above South Mesquite Creek	East_Fork_abv_S_Mesquite_Ck	416.9	9,500	19,700	28,000	39,600	49,100	59,300	76,000	105,300

Location Description	HEC-HMS Element Name	Drainage Area*	50%	20%	10%	4%	2%	1%	0.50%	0.20%
		sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR
East Fork Trinity River below South Mesquite Creek	East_Fork+South_Mesquite_Ck	446.4	10,000	20,500	29,000	41,100	51,000	61,700	79,400	110,600
East Fork Trinity River above Mustang Creek	East_Fork_abv_Mustang_Ck	465.5	9,400	19,000	25,900	35,100	43,700	52,900	66,700	88,800
East Fork Trinity River near Crandall, TX USGS gage	East_Fork_nr_Crandall	484.8	9,600	19,400	26,500	35,800	44,600	53,900	68,100	90,700
East Fork Trinity River above the Trinity River	East_Fork_abv_Trinity_River	484.8	9,200	17,100	22,800	30,500	37,200	44,700	55,500	70,600
Trinity River below the East Fork Trinity River	Trinity River + East Fork	4014.2	27,000	41,600	54,200	80,400	104,100	134,200	166,200	210,600
Trinity River below Red Oak Creek	Trinity_River + Red_Oak_Ck	4245.5	27,100	43,400	55,300	81,000	105,000	135,200	167,700	212,700
Trinity River near Rosser, TX USGS gage	Trinity_River_nr_Rosser	4349.6	25,600	38,900	51,000	74,000	98,700	131,500	164,600	207,300
Trinity River above Cedar Creek	Trinity_River_abv_Cedar_Ck	4349.6	24,700	38,000	50,000	68,300	76,700	105,600	150,100	196,600
Cedar Creek Reservoir Inflow	Cedar Creek Inflow	1010.8	45,200	82,100	106,000	135,000	158,200	182,100	219,900	274,400
Cedar Creek Reservoir Outflow	Cedar Creek Reservoir	1010.8	32,400	55,600	70,000	88,300	105,900	123,700	129,800	140,500
Trinity River below Cedar Creek	Trinity River + Cedar Creek	5360.4	27,600	41,300	53,400	71,600	79,200	112,300	162,400	220,600
Trinity River at Trinidad, TX USGS gage	Trinity_River_at_Trinidad	5759.3	33,300	51,200	68,000	89,100	106,800	125,100	155,800	188,200
Trinity River above Richland Creek	Trinity_Rv_abv_Richland_Ck	6042.8	31,300	48,100	63,500	83,100	99,900	117,300	149,800	187,500
Bardwell Lake Inflow	Bardwell Inflow	174.4	10,400	18,700	23,400	30,700	35,700	41,300	48,500	59,200
Chambers Creek below Mill Creek	Chambers_Ck_J020	511.9	13,600	29,100	40,900	62,200	75,900	88,300	114,200	148,800
Chambers Creek below Waxahachie Creek	Chambers Ck + Waxahachie Ck	621.0	12,800	28,300	39,500	60,200	74,300	86,700	113,500	152,700
Chambers Creek near Rice, TX USGS gage	Chambers_Ck_J030	650.1	12,500	28,000	39,000	59,200	73,300	88,100	110,500	148,800
Richland Creek below Pin Oak Creek	Richland_Ck_J010	395.0	19,000	37,800	50,100	64,800	76,300	87,600	106,900	135,300
Richland Chambers Reservoir Inflow	Richland-Chambers Inflow	1465.5	33,300	64,300	85,700	112,000	133,000	154,500	188,200	237,200

Location Description	HEC-HMS Element Name	Drainage Area*	50%	20%	10%	4%	2%	1%	0.50%	0.20%
		sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR
Richland Chambers Reservoir Outflow	Richland-Chambers Reservoir	1465.5	9,500	26,700	42,700	65,800	86,000	107,400	143,200	193,900
Trinity River below Richland Creek	Trinity River + Richland Ck	7508.3	36,200	64,300	88,100	122,800	150,100	177,200	234,800	304,000
Trinity River above Tehuacana Creek	Trinity_Rv_abv_Tehuacana_Ck	7508.3	35,300	63,300	87,600	122,400	149,500	178,100	234,200	306,200
Trinity River below Tehuacana Creek	Trinity River + Tehuacana Ck	7894.7	38,700	59,000	81,700	124,000	157,800	192,800	259,200	349,800
Trinity River above Big Brown Creek	Trinity_Rv_abv_Big_Brown_Ck	7965.3	37,900	58,600	80,900	120,000	148,400	189,000	254,100	345,000
Trinity River below Big Brown Creek	Trinity River + Big Brown Ck	8001.5	38,200	59,100	81,600	121,000	154,000	190,100	255,900	348,700
Trinity River above Catfish Creek	Trinity_River_abv_Catfish_Ck	8306.6	39,500	60,800	85,300	122,200	153,300	190,100	264,300	367,200
Trinity River below Catfish Creek	Trinity_River + Catfish_Ck	8353.0	39,800	61,400	86,000	123,200	154,200	191,500	266,400	370,700
Trinity River near Oakwood, TX USGS gage	Trinity_River_nr_Oakwood	8593.0	36,300	59,500	81,100	107,400	129,000	152,400	223,500	308,900
Trinity River above Upper Keechi Creek	TrinityRv_abv_UpperKeechi_Ck	8849.7	33,000	54,300	71,800	99,000	121,800	139,500	160,100	235,500
Trinity River below Upper Keechi Creek	Trinity River + Upper Keechi	9358.9	33,700	54,900	72,200	99,700	122,900	140,900	163,700	243,300
Trinity River above Big Elkhart Creek	Trinity_Rv_abv_Big_Elkhart	9359.5	33,600	54,300	72,000	99,500	122,800	140,700	163,600	241,800
Trinity River below Big Elkhart Creek	Trinity River+ Big Elkhart	9502.5	33,100	53,300	70,100	98,000	121,600	139,300	160,600	233,700
Trinity River near Crockett, TX USGS gage	Trinity_River_nr_Crockett	9615.0	33,300	53,900	71,500	98,700	121,900	139,800	160,600	235,000
Trinity River above Lower Keechi Creek	Trinity_Rv_abv_LowerKeech_Ck	9791.7	32,900	48,100	56,600	72,500	96,400	114,900	145,300	181,300
Trinity River below Lower Keechi Creek	Trinity_River+LowerKeechi_Ck	9979.3	32,700	48,200	56,600	72,600	96,700	115,200	145,500	181,500
Trinity River above Bedias Creek	Trinity_River_abv_Bedias_Ck	10374.29	32,600	47,200	54,300	68,600	92,800	110,200	140,400	175,800
Bedias Creek above the Trinity River	Bedias_Ck_abv_Trinity_River	604.3	13,100	32,500	46,800	64,300	76,800	90,800	114,400	147,300

Location Description	HEC-HMS Element Name	Drainage Area*	50%	20%	10%	4%	2%	1%	0.50%	0.20%
		sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR
Trinity River below Bedias Creek	Trinity River + Bedias Ck	10978.5	44,300	69,800	96,100	128,000	150,400	172,300	205,200	251,400
Trinity River at Riverside, TX USGS gage	Trinity River_at_Riverside	11306.7	41,000	61,500	71,800	109,300	133,800	158,700	194,300	249,200
Lake Livingston Inflow	Lake Livingston Inflow	12301.1	77,000	111,100	144,000	193,600	233,400	278,700	333,900	413,400
Lake Livingston Outflow	Lake Livingston	12301.1	38,900	65,700	81,100	100,400	120,700	158,200	210,400	281,800
Trinity River above Long King Creek	Trinity_Rv_abv_Long_King_Ck	12340.5	39,600	67,000	82,800	102,100	123,700	159,400	208,300	277,000
Trinity River at Goodrich, TX USGS gage	Trinity River + Long King Ck	12566.9	40,000	69,000	84,400	104,700	126,400	162,200	211,200	282,700
Trinity River above Menard Creek	Trinity_River_abv_Menard_Ck	12628.0	39,400	59,900	73,600	89,400	101,100	118,200	148,200	207,300
Trinity River below Menard Creek	Trinity River + Menard Ck	12776.2	40,700	64,000	77,400	94,100	107,700	127,500	159,500	220,900
Trinity River at Romayor, TX USGS gage	Trinity_River_at_Romayor	12873.7	40,700	62,900	76,500	93,100	107,000	126,200	157,100	218,100
Trinity River near Moss Hill, TX	Trinity_River_nr_MossHill_TX	12945.7	39,600	59,200	73,800	91,300	104,600	122,000	152,200	208,800
Trinity River at Liberty, TX USGS gage	Trinity_River_at_Liberty	13176.5	34,800	54,500	70,800	90,200	103,700	120,900	151,100	205,300
Trinity River at Wallisville, TX USGS gage	Trinity Bay	13618.4	32,300	45,700	62,400	84,000	98,700	115,300	141,800	188,300

*Drainage area is uncontrolled area downstream of USACE dams.

7.7 ELLIPTICAL STORM VERSUS UNIFORM RAIN FREQUENCY RESULTS

As mentioned at the beginning of this chapter, because the published depth-area reduction curves from TP-40 do not extend beyond 400 square miles, the uniform rainfall method may not always be appropriate for larger drainage areas. Therefore, elliptical frequency storms were computed in HEC-HMS as an alternate method to test against uniform rain results for larger drainage areas.

Figure 7.14 below gives a comparison of the percent difference in the 1% annual chance (100-yr) peak flow estimate from the elliptical storms versus the uniform rainfall method. This percent difference is then plotted versus the drainage area of the point of interest. Though there is some scatter in the difference between methods around the 400 square mile node, one may observe that the results of the two methods generall stay within 10% of one another up to approximately 2,000 square miles. From this example, one may conclude that the uniform rainfall method continues to give a reasonable estimate of frequency peak discharges up to at least 1,000 square miles.

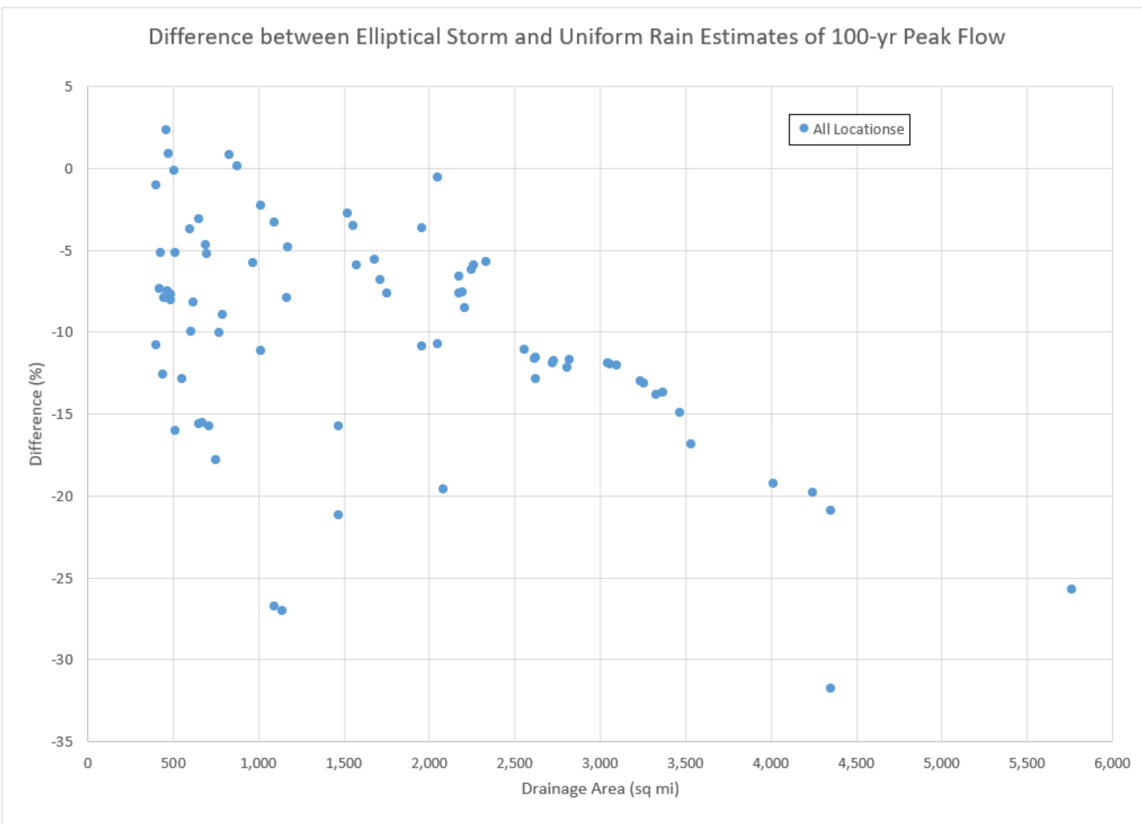


Figure 7.14: Difference (Percent) between Elliptical and Uniform Rain Estimates for the 1% ACE (100yr) Storm Events

8 Riverware Analysis

8.1 INTRODUCTION TO RIVERWARE MODELING

RiverWare is a river system modeling tool developed by CADSWES (Center for Advanced Decision Support for Water and Environmental Systems) that allows the user to simulate complex reservoir operations and perform period-of-record analyses for different scenarios. For the InFRM hydrology studies, Riverware is used to generate a regulated period-of-record by simulating the basin as if the reservoirs and their current rule sets had been present in the basin for the entire time period. Statistical analyses can then be performed on the extended records at the gages.

This report summarizes the Riverware portion of the hydrologic analysis being completed for the InFRM Hydrology study of the Trinity Basin. The following discussion will focus predominately on the calibration, data selection, and operational rule policies, in the simulation-run Riverware model of the Trinity watershed. A detailed explanation of the Trinity watershed period-of-record (POR) hydrology will be in this report. Ultimately, the results of the Riverware analysis hinge on the best available datasets being selected, and that the datasets are not overly susceptible to numerical error. These topics will be discussed in greater detail in the following sections.

8.2 UPDATES TO THE ESISTING POR HYDROLOGY AND OPERATIONS MODELS

Prior to RiverWare, a legacy program called SUPER was used to establish POR hydrology or naturalized local flow datasets. The transition to RiverWare began in 2009. The existing USACE Riverware POR hydrology model had USGS and USACE flow data through 2011. For the InFRM study, gage data was incorporated into the RiverWare operation model through December 31, 2015. A RiverWare POR hydrology model was also created by converting the SUPER POR hydrology model and incorporates gage data from the U.S. Geological Survey (USGS) and U.S. Army Corps of Engineers (USACE) that date back to January 1, 1940.

A decision was made to convert the SUPER POR hydrology model into a RiverWare POR hydrology model at the onset of the InFRM Hydrology Study of the Trinity River Basin. The decision allowed Lake Worth to be incorporated into the RiverWare POR hydrology model and the RiverWare operation model; this was not done previously for SUPER or the RiverWare operation model. RiverWare models particular streams and reservoirs and includes the stream gages found in Table 8.1 below and reservoirs found in Table 8.2.

Table 8.1: Key Stream Gages used in RiverWare Models

Stream Gages	USGS Site Number	USGS Site Name
Fort Worth on Clear Fork	08047500	Clear Fk Trinity Rv at Fort Worth, TX
Fort Worth	08048000	W Fk Trinity Rv at Fort Worth, TX
Grand Prairie abv Mountain Creek	08049500	W Fk Trinity Rv at Grand Prairie, TX
Grand Prairie on Mountain Creek	08050100	Mountain Ck at Grand Prairie, TX
Carrolton	08055500	Elm Fk Trinity Rv nr Carrollton, TX
Grapevine Outflow	08055000	Denton Ck nr Grapevine, TX
Benbrook Outflow	08047000	Clear Fk Trinity Rv nr Benbrook, TX
Dallas	08057000	Trinity Rv at Dallas, TX

Stream Gages	USGS Site Number	USGS Site Name
Crandall	08062000	E Fk Trinity Rv nr Crandall, TX
Navarro Mills Outflow	08063100	Richland Ck nr Dawson, TX
Corsicana	08064500	Chambers Ck nr Corsicana, TX
Richland Chambers Outflow	08064600	Richland Ck nr Fairfield
Trinidad	08062700	Trinity Rv at Trinidad, TX
Oakwood	08065000	Trinity Rv nr Oakwood, TX
Riverside	08066000	Trinity Rv at Riverside, TX
Midway	08065500	Trinity Rv nr Midway, TX
Romayor	08066500	Trinity Rv at Romayor, TX
Richland	08063500	Richland Ck nr Richland, TX
Rosser	08062500	Trinity Rv nr Rosser, TX
Ray Hubbard Outflow	08061750	E Fk Trinity Rv nr Forney
Lewisville Outflow	08053000	Elm Fk Trinity Rv nr Lewisville
Bardwell Outflow	08063800	Waxahachie Ck nr Bardwell

The Trinity River Basin is probably one of the most complicated Basins to analyze with a RiverWare model in Texas. The screenshots of the Riverware model diagram are found in Figure 8.1 and Figure 8.2. The RiverWare operations model includes legacy gage locations that are no longer active. There are dam site locations specified that do not actually exist. These are artifacts of the original SUPER model and impoundment at these areas are unlikely. Additionally, significant pumpage from and into the Trinity River Basin were accounted for as seen in the screenshots.

For this study, flow data were updated through December 31st, 2015. Both the RiverWare POR hydrology and operations models begin on January 1st, 1940. Rulesets were written for the operations model to mimic conservation releases. As pumpage demands and releases have changed throughout the years due to differing demands, the ruleset attempted to recreate recent pumpage demands and releases and to match approximately the last 10 years of record, from 2005-2015.

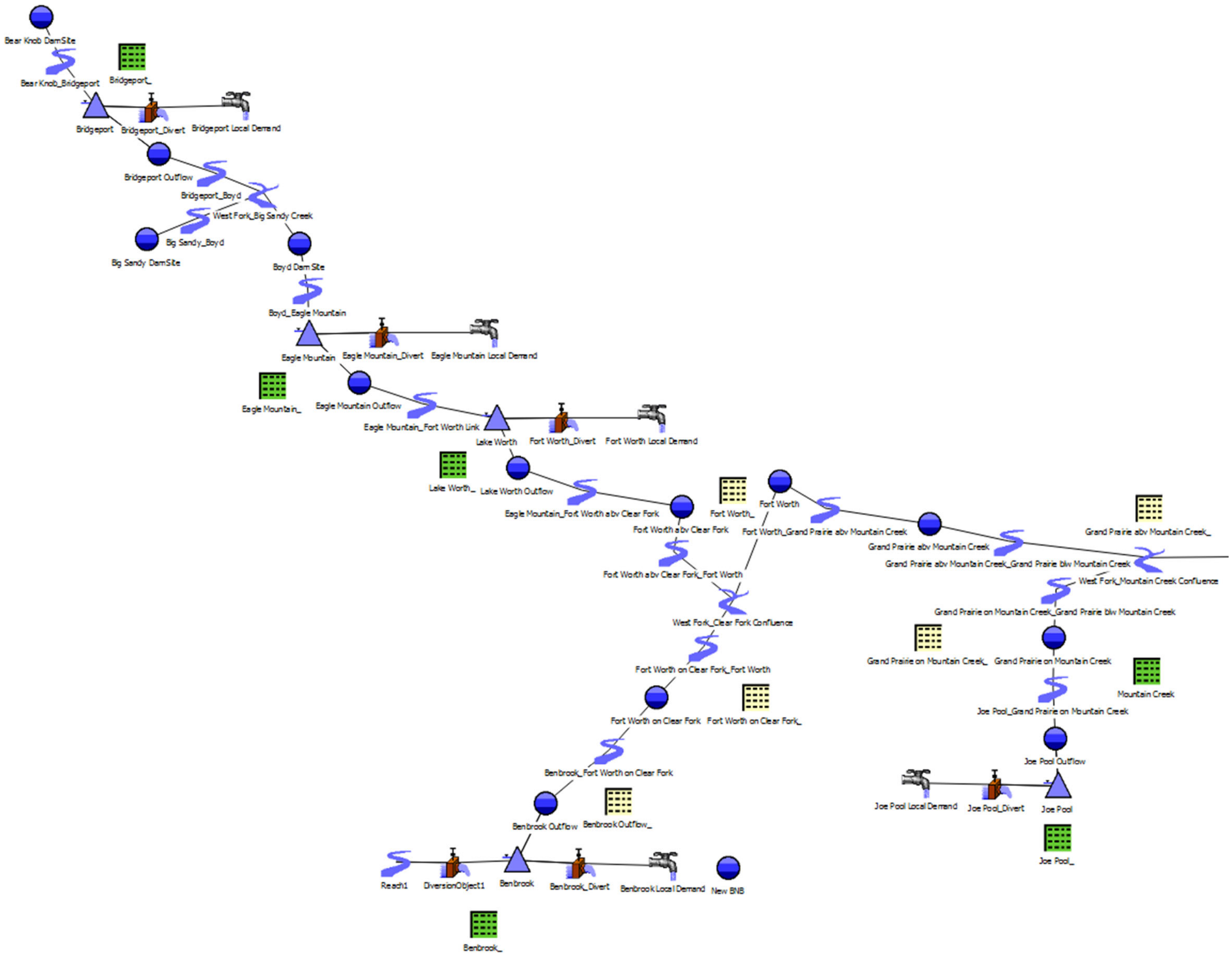


Figure 8.1: RiverWare Diagram of West Trinity River Basin

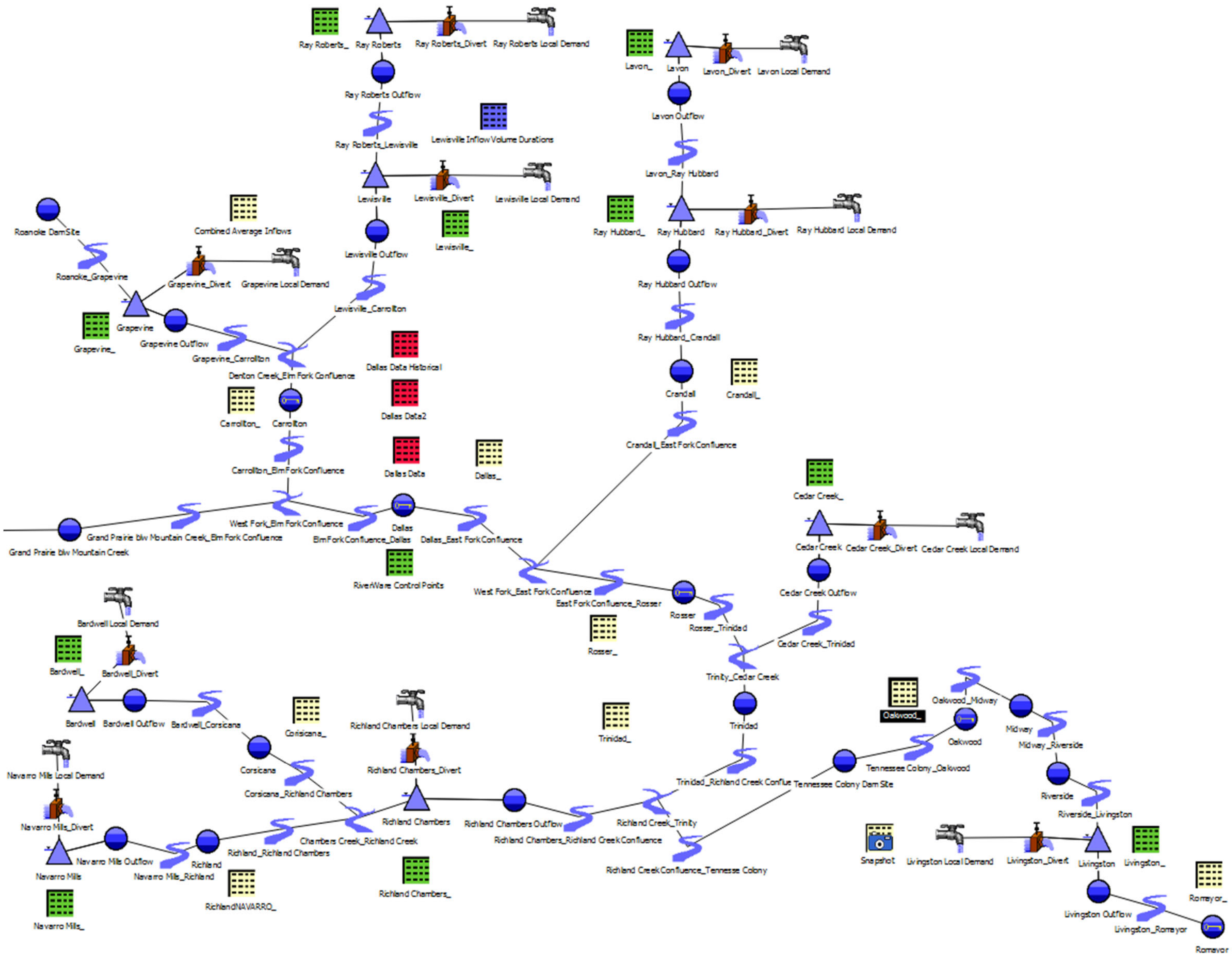


Figure 8.2: RiverWare Diagram of East Trinity River Basin

8.3 DATA SOURCES USED IN THE RIVERWARE MODEL

The primary data used in the hydrology model is daily USGS flows and USACE reservoir inflows. USGS gage data were often found online, but at times were found within USACE records. Evaporation rates were specified for each reservoir based on USACE calculated evaporation. The pumpage data are assimilated from various stakeholders. Pumpage and releases are implemented using rulesets that reflect the last 10 years of record, as well as evaporation.

8.4 METHODOLOGY USED TO DEVELOP THE POR HYDROLOGY

The important methods used to develop the POR hydrology for the Trinity River Watershed in this report are the drainage-area-ratio method, reservoir inflow calculation, and reservoir inflow smoothing algorithm. The methods will be explained in greater detail in the following paragraphs.

Rarely is there a watershed study where sufficient and consistent gage datasets exist. Incomplete gage datasets for both stream gages and reservoirs gages can be attributed to budget limitations and anthropogenic changes, i.e. installation of reservoirs. To reconcile the inconsistent datasets, drainage area ratios are used to extrapolate and interpolate gage datasets. The drainage-area-ratio method (Gupta, 2008) provides a numerical approximation of the missing gage data, using gage datasets upstream or downstream on the same river (Equation 1).

$$Q_y = \frac{Q_x}{A_x} A_y$$

Equation 1: Drainage-Area-Ratio Method

$Q_y = Flow\ at\ gaged\ site\ Y\ of\ drainage\ area\ A_y\ [L^3 / T]$

$Q_x = Flow\ at\ gaged\ site\ X\ of\ drainage\ area\ A_x\ [L^3 / T]$

$A_y = Drainage\ area\ of\ unavailable\ gaging\ station\ record\ Y\ [L^2]$

$A_x = Drainage\ area\ of\ available\ gaging\ station\ record\ X\ \ [L^2]$

The numerous array of reservoir inflow calculations tolerate for thoroughness, as well as disjointedness. All reservoir inflow calculations utilize a mass balance approach. The method selection for the calculation of reservoir inflow is subjective. There are two methods used to calculate reservoir inflow; they will be called the “net evaporation reservoir inflow method” and the “evaporation reservoir inflow method” which is the method applied to USACE datasets. The net evaporation reservoir method incorporates precipitation, whereas, the evaporation reservoir inflow calculation does not incorporate precipitation into the reservoir inflow calculation (Equation 2 and Equation 3).

$$I = \Delta S + E + R + Q_{total} - P$$

Equation 2: Net Evaporation Reservoir Inflow Method

$I = Inflow\ into\ the\ reservoir\ [L^3/\ T]$

$\Delta S = Change\ in\ reservoir\ storage\ [L^3/\ T]$

$E = Evaporation\ from\ the\ reservoir\ [L^3/\ T]$

$R = Releases\ from\ the\ reservoir\ [L^3/\ T]$

$Q_{total} = Total\ pumpage\ out\ of\ the\ reservoir\ [L^3/\ T]$

$P = Precipation\ on\ the\ reservoir\ [L^3/\ T]$

$$I = \Delta S + E + R + Q_{total}$$

Equation 3: Evaporation Reservoir Inflow Method

$I = Inflow\ into\ the\ reservoir\ [L^3/\ T]$

$\Delta S = Change\ in\ reservoir\ storage\ [L^3/\ T]$

$E = Evaporation\ from\ the\ reservoir\ [L^3/\ T]$

$R = Releases\ from\ the\ reservoir\ [L^3/\ T]$

$Q_{total} = Total\ pumpage\ out\ of\ the\ reservoir\ [L^3/\ T]$

The calculated reservoir inflow is subject to measurement error and numerical error. The evaporation parameter is arguably the most difficult parameter to estimate when calculating reservoir inflow. The uncertainty in measurement often leads to negative reservoir inflow values, which violates the conservation of mass principle. The reservoir inflow values are numerically smoothed by scaling positive inflows and rectifying negative inflows to resolve this inconsistency of negatives. The smoothed inflow algorithm is applied over a monthly time period with a daily time step (Equation 4, Equation 5, Equation 6, and Equation 7). There are additional inflow smoothing methods available, but this method is sufficient to resolve negative reservoir inflows in this case.

$$Montly\ Total\ Inflow = \sum_{i}^{i_f} I_i$$

Equation 4: Monthly Total Inflow Method

$$\text{Nonnegative Inflow} = \begin{Bmatrix} if\ I_i < 0 \\ 0 \\ else \\ I_i \end{Bmatrix}$$

Equation 5: Nonnegative Inflow Method

$$Montly\ Total\ Nonnegative\ Inflow = \sum_{i}^{i_f} Nonnegative\ Local$$

Equation 6: Monthly Total Nonnegative Inflow Method

$$Smoothed\ Inflow = \begin{Bmatrix} if\ Monthly\ Total\ Inflow < 0\ OR\ Montly\ Total\ Nonnegative\ Inflow = 0 \\ Nonnegative\ Inflow * 0 \\ else \\ Nonnegative\ Inflow * \dfrac{Monthly\ Total\ Inflow}{Montly\ Total\ Nonnegative\ Inflow} \end{Bmatrix}$$

Equation 7: Smoothed Inflow Method

$I = Inflow\ into\ the\ reservoir\ on\ the\ i^{th}\ day\ [L^3/\ T]$

$i = i^{th}\ day\ of\ the\ month\ []$

$i_f = last\ day\ of\ the\ month\ []$

$Montly\ Total\ Nonnegative\ Inflow = Summation\ of\ the\ monthly\ nonnegative\ inflows\ [L^3/\ T]$

$Montly\ Total\ Inflow = Summation\ of\ the\ monthly\ reservoir\ inflows\ [L^3/\ T]$

$\text{Nonnegative Inflow} = \text{A nonnegative dataset of the reservoir inflows } [[L^3/\ T]\text{: } [L^3/\ T]]$

$\text{Smoothed Inflow} = \text{A smoothed dataset of the reservoir inflows } [[L^3/\ T]\text{: } [L^3/\ T]]$

The methods presented above along with the RiverWare modeling software have permitted for the development of POR hydrology for the Trinity River Basin Watershed. The following section will describe how these methods were implemented within the framework of the RiverWare modeling software and the precursor to the RiverWare modeling software.

8.5 RIVERWARE OPERATIONAL MODEL APPLICATION

The POR hydrology needed to evaluate the Trinity River Watershed requires the use of numerical models.. RiverWare 7.0.4 was used to analyze the hydrologic processes of reservoirs within the Trinity River

Watershed. The hydrologic analysis includes the use of a multiple-run and simulation-run RiverWare model. The multiple-run RiverWare model produced the POR hydrology from January 1940 to December 2015 for all stream and reservoir gage sites. The POR hydrology is the naturalized local flows, where major anthropogenic impacts have been removed, including effects of reservoir regulation. The RiverWare POR hydrology model was compared to the legacy SUPER model and proved successful. The simulation-run RiverWare model used the POR hydrology datasets to simulate flow within the Trinity River Watershed with reservoir regulation policies incorporated for the entire POR, which will be used in the statistical frequency analysis portion of this study.

The process for developing POR hydrology, for the reservoirs and control points or stream gages of interest, is to assimilate historical reservoir inflow and stream flow datasets, then implement drainage-area-ratio methods and reservoir inflow smoothing algorithms in a multiple-run RiverWare model to numerically solve for the POR hydrology. Analyzing regulated flows at gages or control points, pool elevations and operational release over the POR requires the POR hydrology and reservoir operational policies and rule sets incorporated into a simulation-run RiverWare operation model. The reservoir operational policies and rule sets applied to reservoirs can be compared to historical pool elevations, releases, and local inflows to verify consistency with historical datasets. Ultimately the policies and rule sets can be applied to the POR hydrology to establish synthetic pool elevation and reservoir operation before the reservoirs existed.

When developing the RiverWare POR Hydrology, the impoundment dates of major reservoirs are important to incorporate. A list of key impoundments in the Trinity River Basin are found in Table 8.2. The dates are incorporated into the rule-based simulation logic of RiverWare to ensure appropriate estimation of local naturalized flows. In addition to the impoundment dates, stream gage installation and removal dates are important for estimation.

Table 8.2: Date of Impoundment for Dams in the Trinity Basin

Dam Name	Impoundment Date
Bardwell	December 1965
Benbrook	October 1952
Bridgeport	April 1932
Cedar Creek	July 1965
Eagle Mountain	February 1934
Worth	June 1914
Grapevine	May 1952
Joe Pool	January 1986
Lavon	October 1953
Lewisville	November 1954

Dam Name	Impoundment Date
Livingston	October 1968
Mountain Creek	January 1937
Navarro Mills	October 1962
Ray Hubbard	January 1968
Ray Roberts	October 1987
Richland-Chambers	July 1987

8.6 RIVERWARE OPERATIONAL OUTPUT RESULTS

The final product of this analysis, is the POR pool elevations for the reservoirs and POR stream flows from Jan 1940 to Dec 2015. The datasets and numerical methods were vetted and the results were crosschecked thoroughly with the historical datasets. The stream flow results were given to the USGS for additional statistical analysis.

The RiverWare simulated POR stream flow results (depicted in blue) were compared to measured USGS gaged flow (depicted in red). One example of this is seen below in Figure 8.3. The complete list of comparison plots can be found in Appendix D – Riverware Analysis. The locations have good correspondence between RiverWare and UGSG flow values. The subtle deviations can be attributed to the way RiverWare operations are unrealistically exact and how USACE reservoir regulators make decisions with additional insight. The large deviations and missing data can be attributed to downstream gaging prior to impoundment and lack of a recording gage.

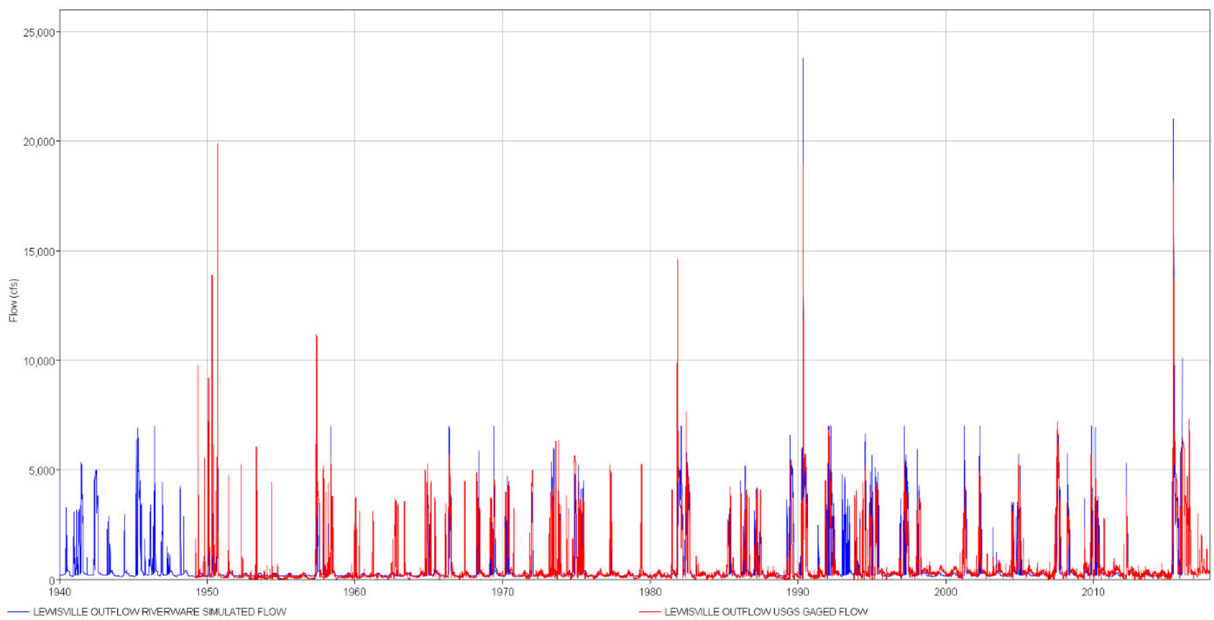


Figure 8.3: The Lewisville Outflow for RiverWare Simulated Flow (Blue) compared to USGS Historic Flow (Red).

8.7 STREAMGAGE DATA AND STATISTICAL FLOOD FREQUENCTY RESULTS

For the statistical analysis of the RiverWare modeling results, USGS staff analyzed the simulated hourly peak streamflows for 22 USGS streamflow-gaging stations (streamgages) that were included in the RiverWare model. The analyzed streamgages are listed in Table 8.3. A peaking factor was applied to the RiverWare daily time-step data. A peaking factor is needed to convert the daily peak flows to hourly (instantaneous) peak flows. A peaking factor of 'N/A' signifies that no peaking factor was applied to that dataset. It was determined that the difference between daily and instantaneous annual peak discharge was negligible in regard to the present analysis. If two peaking factors were applied to the gage, they are both listed as well as the inflection point in log10 scale. Peak streamflow frequency analyses were conducted at the gages using the simulated hourly annual peak flow data for the entire period of record provided by RiverWare output. In addition to the analyses performed on the simulated hourly peaks, the same analyses were repeated for the simulated daily peaks and then compared to the flood flow frequency results, which were based on observed instantaneous peak streamflows for the USGS historic analyses discussed in Appendix A – Statistical Hydrology.

Table 8.3: USGS NWIS Station Number and Name, Abbreviated Name in Report, Stream Name, Latitude, Longitude, and Start (and End if Applicable) Date of Historic Peak Record for the 22 Gages Analyzed.

Station number and name	Name in report	Stream name	Latitude	Longitude	Historic peak record begins (ends)	Peaking Factor
08047000 Clear Fork Trinity River near Benbrook, Tex.	Benbrook gage	Clear Fork Trinity River	32.6651	-97.4420	1948	y=1.022x
08047500 Clear Fork Trinity River at Fort Worth, Tex.	Fort Worth Clear Fork gage	Clear Fork Trinity River	32.7324	-97.3589	1922	log10(daily) > 3.25: y=0.683x+1.650 log10(daily) < 3.25: y=0.834x+1.209
08048000 West Fork Trinity River at Fort Worth, Tex.	Fort Worth West Fork gage	West Fork Trinity River	32.7610	-97.3325	1921	y=0.627x+1.713
08049500 West Fork Trinity River at Grand Prairie, Tex.	Grand Prairie gage	West Fork Trinity River	32.7625	-96.9944	1925	log10(daily) > 4: y=1.153x-0.593 log10(daily) < 4: y=0.782x+0.914
08050100 Mountain Creek at Grand Prairie, Tex.	Mountain Creek gage	Mountain Creek	32.7499	-96.9261	1961	y=1.065x
08053000 Elm Fork Trinity River near Lewisville, Tex.	Lewisville gage	Elm Fork Trinity River	33.0457	-96.9611	1950	N/A
08055000 Denton Creek near Grapevine, Tex.	Denton Creek gage	Denton Creek	32.9871	-97.0128	1948	y=0.635x+1.35
08055500 Elm Fork Trinity River near Carrollton, Tex.	Carrollton gage	Elm Fork Trinity River	32.9660	-96.9445	1908	log10(daily) > 3.5: y=0.987x+0.141 log10(daily) < 3.5: y=0.829x+0.813
08057000 Trinity River at Dallas, Tex.	Dallas gage	Trinity River	32.7749	-96.8219	1904	y=1.006x+0.032
08061750 East Fork Trinity River near Forney, Tex.	Forney gage	East Fork Trinity River	32.7743	-96.5036	1973	y=0.796x+0.998
08062000 East Fork Trinity River near Crandall, Tex.	Crandall gage	East Fork Trinity River	32.6387	-96.4853	1950	log10(daily) > 4: y=1.088x-0.323 log10(daily) < 4: y=0.955x+0.231
08062500 Trinity River near Rosser, Tex.	Rosser gage	Trinity River	32.4265	-96.4630	1908	y=1.006x
08062700 Trinity River at Trinidad, Tex.	Trinidad gage	Trinity River	32.1477	-96.1025	1965	N/A
08063100 Richland Creek near Dawson, Tex.	Dawson gage	Richland Creek	31.9385	-96.6814	1961	y=1.026x
08063500 Richland Creek near Richland, Tex.	Richland gage	Richland Creek	31.9507	-96.4214	1939	y=1.024x
08063800 Waxahachie Creek near Bardwell, Tex.	Bardwell gage	Waxahachie Creek	32.2435	-96.6403	1964	N/A
08064100 Chambers Creek near Rice, Tex.	Rice gage	Chambers Creek	32.1985	-96.5203	1984	log10(daily) > 4: y=1.230x-0.856 log10(daily) < 4: y=0.926x+0.380
08064600 Richland Creek near Fairfield, Tex.	Fairfield gage	Richland Creek	31.9524	-96.0975	1973 (1981)	N/A
08065000 Trinity River near Oakwood, Tex.	Oakwood gage	Trinity River	31.6485	-95.7894	1890	N/A
08065500 Trinity River near Midway, Tex.	Midway gage	Trinity River	31.0746	-95.6994	1940 (1970)	N/A
08066000 Trinity River at Riverside, Tex.	Riverside gage	Trinity River	30.8594	-95.3988	1903 (1968)	N/A
08066500 Trinity River at Romayor, Tex.	Romayor gage	Trinity River	30.4252	-94.8508	1924	N/A

The peaking factor used for this study was developed using a log-log regression between USGS hourly and daily peak flows (Figure 8.4). The linear fit is plotted along with its formula, and an equal value line is plotted for reference. The period of record analyzed for the peaking factor formulation was truncated to the period of record applicable to the regulated conditions present in the RiverWare model. For example, Figure 8.4 shows the peaking factor formulation for the Fort Worth West Fork streamgage. The analysis of hourly data as a function of the daily data was restricted to peaks after the impoundment of Benbrook Lake in 1952. In addition to filtering for regulated conditions, additional analysis ensured that USGS observed daily and hourly peaks occurred on the same date.

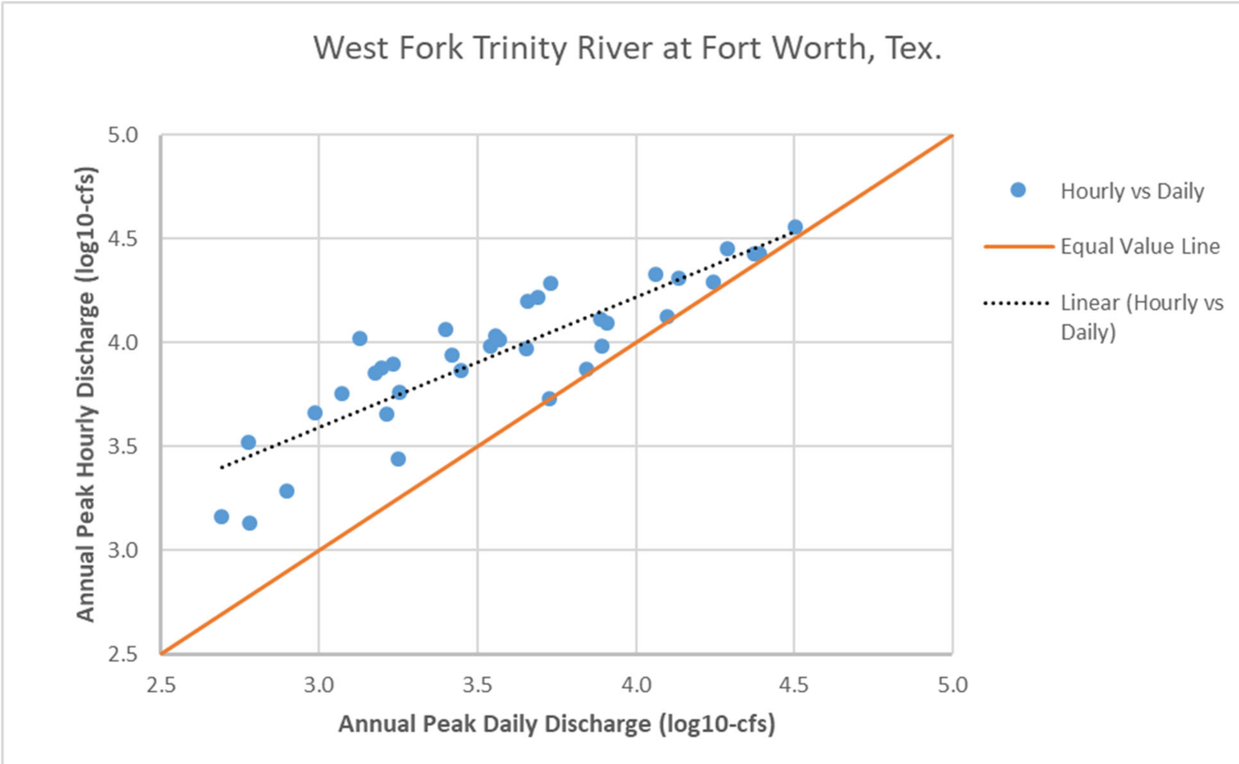


Figure 8.4: Plot of USGS Hourly Historic Annual Peak Streamflow vs. Daily Historic Annual Peak.

At five of the analyzed gage locations (Fort Worth Clear Fork, Grand Prairie, Carrollton, Crandall, and Rice gages), a separate flow regime was observed in the upper end of the hourly vs. daily peak flow relationship, and two peaking factors were developed for lower and upper daily peak flows. For example, Figure 8.5 shows the two separate relationships observed for the Grand Prairie gage, and the two peaking factors derived from these separate relationships. The two linear fit lines are plotted along with their formulae, and an equal value line is plotted for reference. The first peaking factor was applied to simulated daily peak flows less than 10,000 ft^3/s, whereas the second peaking factor was applied to simulated daily peak flows greater than 10,000 ft^3/s. The inflection point between these two peaking factors is unique to each gage. Please refer to Table 8.3 for the inflection point at each gage. The need for two peaking factors at several gage locations highlights a change in streamflow characteristics for the greatest magnitude events.

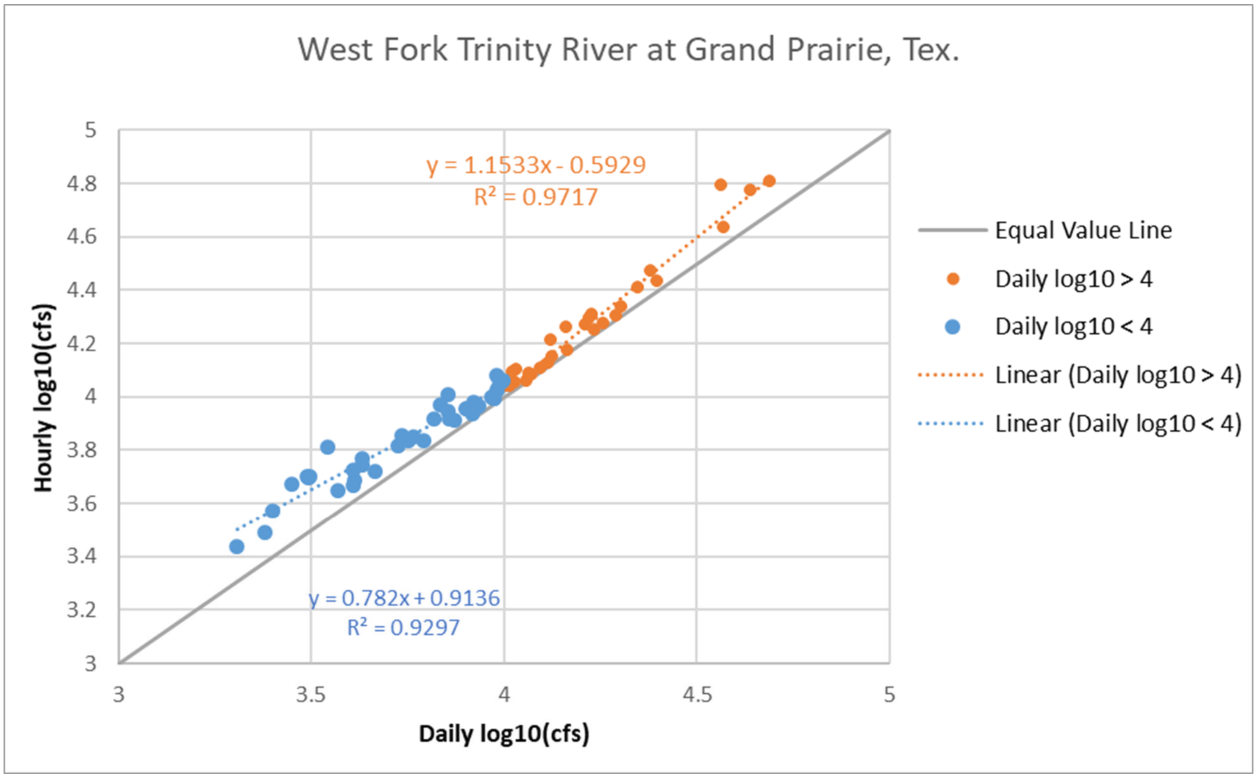


Figure 8.5: Plot of USGS Hourly Historic Annual Peak Streamflow vs. Daily Historic Annual Peak Streamflow for West Fork Trinity River at Grand Prairie.

For four of the analyzed gages (Denton Creek, Forney, Dawson, and Bardwell gages), regulation rulesets in RiverWare were deemed too strict for real-world conditions. Peak streamflow output from the model was highly regulated, resulting in several “steps” of regulated peaks, which did not provide adequate information for a comparison to the historic frequency analysis. Because RiverWare was designed as a reservoir operations model and not a hydraulic model, it is designed to follow a strict set of rules for reservoir operations that may not reflect the more nuanced and complex approach reservoir operators follow for releases. As a result, streamflows, and consequently peak stream flows, downstream of reservoir or control point objects in RiverWare will be more uniform than in reality and more optimistic in a control structure’s ability to regulate extreme events. Therefore, RiverWare simulated peak streamflow frequency curves can generally be expected to provide lower estimates than the historic analysis presented in Appendix A – Statistical Hydrology. Though this may be perceived as a failure of the model, and in fact it has been deemed so in several gage locations, the simulated results may still provide valuable information for frequency analyses in the Trinity basin. Not all the gages show these increased effects of regulation and provide peak streamflow estimates similar to those observed in the historic record. In addition, the RiverWare results may be seen as lower bounds to exceedance probabilities in the basin because they represent the best-case, ideally regulated scenario for peak streamflows in the basin.

The USGS (England et al., 2018) (Bulletin 17C) provides guidance for computation of peak streamflow frequency. The Bulletin 17C methodology is already implemented in USACE HEC-SSP software (Version 2.1.1; USACE, 2017). Bulletin 17C incorporates the expected moments algorithm (EMA), which allows for the incorporation of more complicated or subjective measurements such as paleo-hydrology, interval peaks, and sophisticated gap-infill for years of missing annual peak streamflow records. EMA also include mathematically rigorous computation of uncertainty bounds based on implicit recognition that the skew coefficient is itself uncertain. This was not a feature of Bulletin 17B.

The 17C analysis also advised on use of the multiple Grubbs-Beck low outlier test, which is capable of identifying many potentially influencing low floods (PILFs). The multiple Grubbs-Beck test is a substantial improvement on the single Grubbs-Beck test used in Bulletin 17B (Grubbs & Beck, 1972). The presence of low outliers is endemic in Texas flood hydrology (Asquith et al., 1995). Low outliers within a time series of peak streamflow are anticipated to be too small to be representative of large rainfall and runoff events. The multiple Grubbs-Beck test (MGBT), which is available in the aforementioned USACE software package, is suitable for Texas hydrology. In the statistical computations, low outliers are conditionally truncated, but not removed, from the sample. Overall improved fit of the LPIII distribution in the right or high magnitude tail of the fitted distribution is achieved by low outlier detection.

Peak streamflow analyses for this study were made using the HEC-SSP software (USACE, 2016). The HEC-SSP software uses the three-parameter, log-Pearson type III (LPIII) probability distribution, and the use of this distribution represents a type of standard of practice in the United States and is consistent between Bulletins 17B and 17C. The first and second parameters of the LPIII are the arithmetic mean and standard deviation, and the third parameter of the LPIII is skew. For the estimate of skew, the sample skew computed for the data at each streamgage location was used by HEC-SSP using the “station skew” option. This skew option was selected because there exists no definitive replacement for the generalized skew for the circumstances of analyses described in this chapter. With select exceptions, the station skew option was used throughout the analyses. Unless otherwise noted in Table 8.4, the period of record available for the streamgages was deemed sufficient enough not to raise concerns on general reliability of the statistical computations themselves.

Table 8.4: USGS NWIS Station Number and Name, Abbreviated Name in Report, Regional Skew (Unitless), Regional Skew Mean Square Error (MSE - unitless), and HEC-SSP Adopted Skew for the Gages Not Using the Station Skew Option.

Station number and name	Name in report	Regional Skew	Regional Skew MSE	HEC-SSP Adopted Skew
08047000 Clear Fork Trinity River near Benbrook, Tex.	Benbrook gage	0.100	0.40	-0.201
08062000 East Fork Trinity River near Crandall, Tex.	Crandall gage	0.000	0.40	-0.363

After an analysis of the data listed in Table 4, it was determined that the station skew did not adequately fit the greatest simulated peak streamflow events on record. Highly truncated periods of record because of higher low-outlier thresholds (such as that seen in the Crandall streamgage data) or data heavily influenced by regulation (such as that seen in the Benbrook streamgage data) required the station skew value calculated by HEC-SSP to be weighted by a regional skew to account for this limited information on natural peak flows at the gages. Regional skew values shown by Judd et al. (1996) were used to fit the simulated data, although these values should be taken with some uncertainty because of the use of simulated instead of historic peak streamflow data for most of the streamgages listed in Table 8.4. The weighted regional skew option was applied to both the simulated hourly and daily peak flow data at each of the RiverWare gages listed in Table 8.4. Results from the Trinity River at Dallas USGS gage are included below. The complete set of results can be found in Appendix D – Riverware Analysis.

00057000 Trinity River at Dallas, Texas

The simulated streamflow record for the Dallas streamgage is 1940–2015. The 1990 peak streamflow for the simulated hourly data was 89,058 ft^3/s, which is the simulated peak of record. The historic data extends back to 1904, which means that the historic data contains a mix of flow regimes, with various upstream reservoirs constructed over the past century and continual development in the metro area increasing urban runoff. Figure 8.6 shows the peak streamflow data for the simulated and historic data.

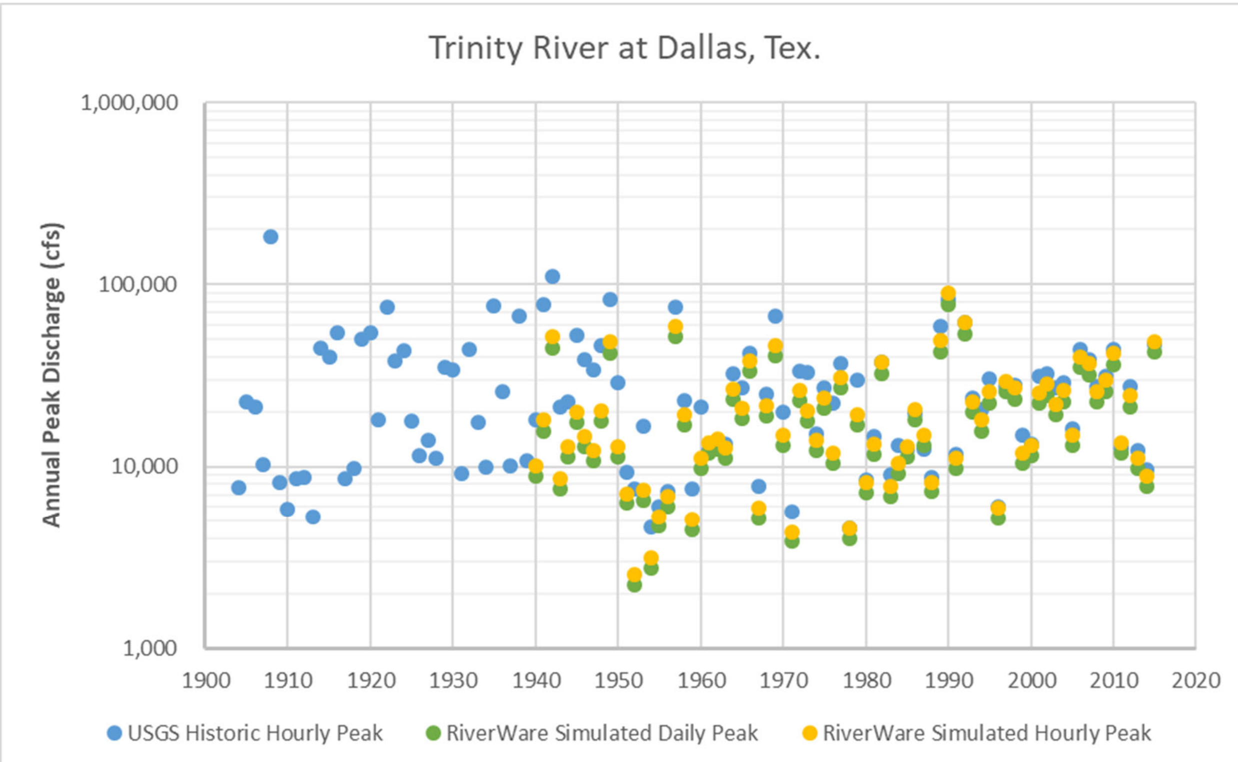


Figure 8.6: USGS Historic Hourly Peak Streamflows, RiverWare Daily Peak Streamflows, and RiverWare Hourly Peak Streamflow Data for Gage 08057000 Trinity River at Dallas.

The LPIII computed peak streamflow frequency curve for the Dallas streamgage simulated hourly data is shown in Figure 8.7. For the Dallas gage, the MGBT did not compute a low-outlier threshold. Apart from a few “shifts” in the data at about 10,000, 15,000, and 35,000 ft^3/s, the ordered events show a consistent upward trend, resulting in a more linear fitted frequency curve with a relatively small skew.

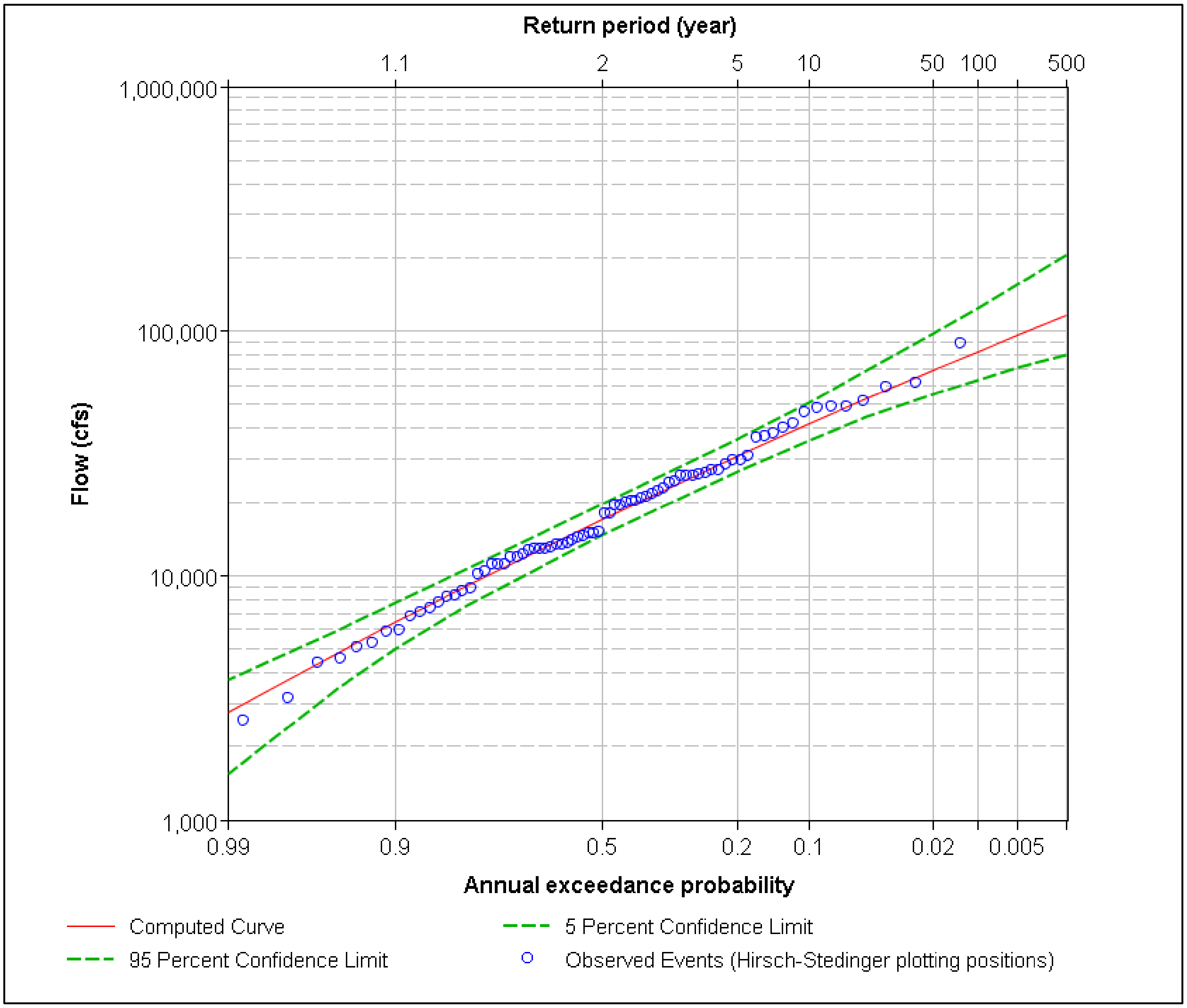


Figure 8.7: Peak Streamflow Frequency using Log-Pearson Type III Distribution for Gage 08057000 Trinity River at Dallas. Hourly RiverWare Output from Screenshot of USACE HEC-SSP Software.

Figure 8.8 compares the LPIII computed peak streamflow frequency curves for the simulated hourly, simulated daily, and USGS historic peak streamflow data computed for the Dallas streamgage. Because the Trinity River at Dallas is a much larger stream not as susceptible to flash floods, there is little difference between the simulated hourly and simulated daily fitted frequency curves. At 0.1 AEP (10-year return interval) and below, the historic and simulated fitted frequency curves trend closer together until they are nearly identical. However, the two curves diverge near the 0.5 AEP because of a greater negative skew in the simulated curve. This could be caused by simulated regulation in RiverWare successfully capturing and regulating lower peak flows in the model's simplified ruleset.

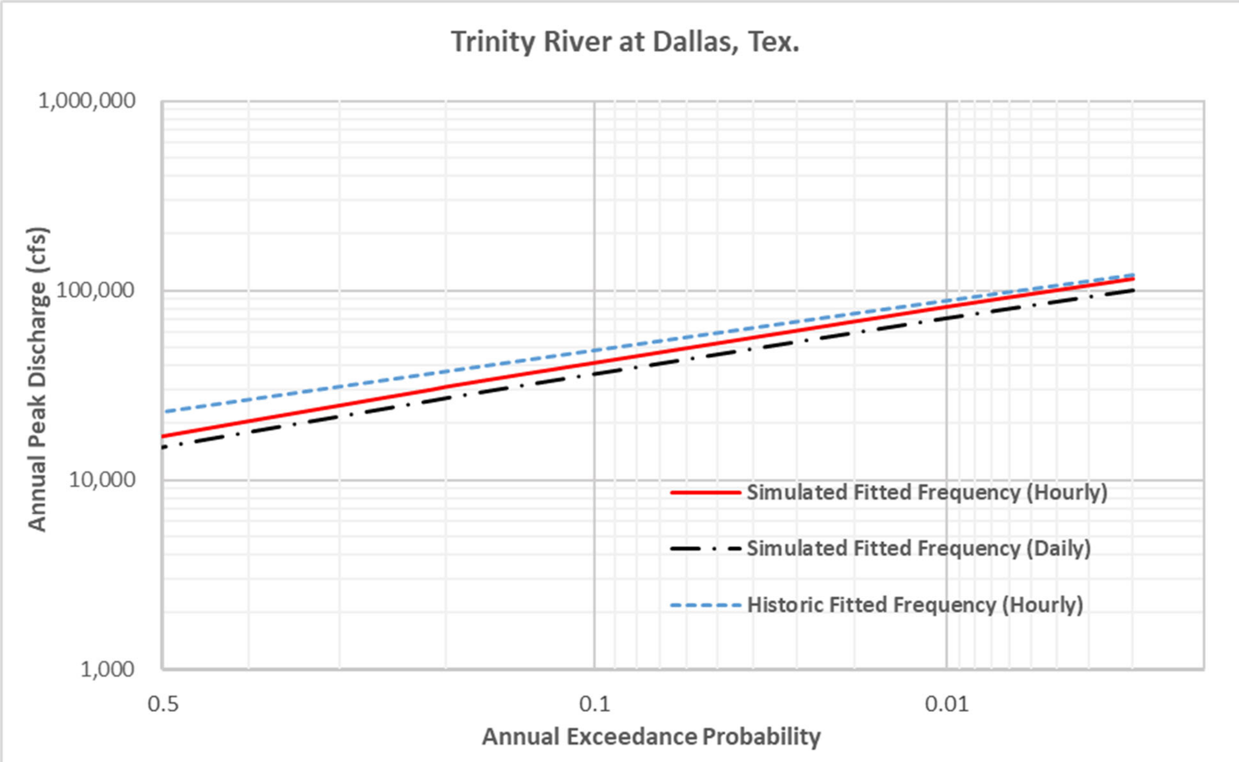


Figure 8.8: Comparison of Log-Pearson Type III Computed Peak Streamflow Frequency Curves for the Simulated Daily, Simulated Hourly, and Historic Hourly Data for Gage 08057000 Trinity River at Dallas.

Table 8.5 summarizes the results of the frequency analysis for the hourly peak streamflows for the 18 streamgages in the Trinity River watershed analyzed for this study. Four were not included because of the influence of regulation in RiverWare failing to match historic data. This issue arose quite frequently in the Trinity watershed, where there are many flood control structures and regulated sections of river. RiverWare was designed as a reservoir operations modeling software, so it will attempt to find a regulated solution to any given inflow based on a set of rules. Despite a modeler's best efforts, these rules can never be as complex or nuanced as the daily decisions being made by reservoir operators in response to a storm event or flooding. Additionally, RiverWare was not specifically designed to model rainfall, runoff, tributary inflow, or other hydrologic processes that contribute to flooding. Instead it routes a user-specified input through a system of regulation objects that simulate a watershed. Therefore, RiverWare modeling results can be expected to be optimistic about capturing peak streamflow events with regulation rulesets, producing lower peak streamflow estimates. This does not necessarily mean that it fails as an analytical tool, but rather should be compared to the other peak streamflow frequency analyses in this report with caveats. The RiverWare model does not produce unrealistic or unreliable results, but rather provides lower bounds to the peak streamflow frequency analysis, based on ideally regulated flows in the Trinity basin.

Differences between the simulated hourly and simulated daily fitted frequency curves diminish downstream, a signal of changing stream characteristics. As the Trinity River increases in size, it is less susceptible to flash floods, and peak streamflow events are typically sustained over the course of the entire day and do not peak sharply over a short period of time.

The effects of regulation on the watershed also diminish downstream on the Trinity River. Regulation has a more nuanced effect on the Trinity further downstream where it is not susceptible to flash floods, but most of the flood control reservoirs in the basin are upstream in the Dallas-Fort Worth metropolitan (metroplex) area.

The fitted frequency results for gages on the Trinity River increase markedly throughout the metroplex. This is most likely because of two factors. First, increased urbanization in the metroplex has led to a large percentage of impermeable surfaces, increasing runoff in the area. Second, the Trinity River coalesces from multiple tributaries in the metroplex (Clear Fork, West Fork, Elm Fork, and East Fork), each contributing a measurable amount of flow to the main stem. Past the Rosser gage, the incremental increase in the fitted frequency curve slows, and even decreases in some cases as the river leaves the heavily urbanized metroplex and the tributaries entering the Trinity have a lower proportional discharge than that of the main stem, so their effects are not as evident. Another reason for the stabilization of the frequency curve could be the attenuation of the flood wave based on the shape of the basin. Beyond the Richland-Chambers watershed, tributaries to the Trinity River appear to have a negligible effect on peak flows, and the Trinity becomes a transport corridor with a declining flood wave.

The Richland-Chambers watershed is the largest subbasin of the Trinity downstream of the Dallas-Fort Worth metroplex. Five gages in this subbasin were analyzed for this report. The Richland-Chambers watershed is a much smaller watershed than the overall Trinity River watershed, which means that the Richland-Chambers creeks are more susceptible to flash floods and peak flows are typically sustained for only a few hours. Because of this, Richland-Chambers gages generally have higher peaking factors than those on the Trinity River mainstem. Reservoirs in the watershed help mitigate the effects of flooding, and evidence of this is seen in the step-wise ordered peak events and difference in the historic and simulated hourly fitted frequency curves such as that of the Richland gage.

Table 8.5: Statistically Estimated Annual Peak Streamflow Frequency Results for the Twenty-Two USGS Streamflow-Gaging Stations in the Trinity River Basin Based on USACE HEC-SSP B17C Computations.

Station number and name and stramflow estimate type	Flood flow frequency by annual exceedence probability (AEP)							
	AEP 0.500 (ft^3/s)	AEP 0.200 (ft^3/s)	AEP 0.100 (ft^3/s)	AEP 0.050 (ft^3/s)	AEP 0.020 (ft^3/s)	AEP 0.010 (ft^3/s)	AEP 0.005 (ft^3/s)	AEP 0.002 (ft^3/s)
Clear Fork Trinity River near Benbrook, Tex.								
Lower 95%-CI	628	2,171	3,204	4,265	5,781	7,008	8,294	10,069
Estimate	**1,165**	**2,654**	**4,007**	**5,576**	**8,007**	**10,132**	**12,514**	**16,081**
Upper 95%-CI	1,398	3,363	5,525	8,648	14,750	21,134	29,262	43,086
Clear Fork Trinity River at Fort Worth, Tex.								
Lower 95%-CI	5,791	9,730	12,409	14,920	17,931	19,955	21,777	23,920
Estimate	**6,626**	**11,093**	**14,236**	**17,318**	**21,365**	**24,425**	**27,493**	**31,563**
Upper 95%-CI	7,559	12,741	16,725	21,284	28,548	35,103	42,722	54,759
West Fork Trinity River at Fort Worth, Tex.								
Lower 95%-CI	7,669	13,119	17,103	21,033	26,093	29,801	33,411	38,046
Estimate	**8,759**	**15,028**	**19,848**	**24,924**	**32,133**	**38,014**	**44,295**	**53,252**
Upper 95%-CI	10,002	17,463	23,969	31,843	44,780	56,814	71,163	94,402
West Fork Trinity River at Grand Prairie, Tex.								
Lower 95%-CI	7,550	13,682	18,956	24,829	33,637	41,174	49,539	61,996
Estimate	**8,734**	**16,099**	**22,900**	**31,174**	**44,969**	**58,073**	**73,988**	**100,281**
Upper 95%-CI	10,102	19,518	29,903	45,760	80,903	124,749	192,276	340,051
Mountain Creek at Grand Prairie, Tex.								
Lower 95%-CI	4,239	7,941	10,219	12,022	13,577	14,313	14,817	15,256
Estimate	**5,094**	**9,201**	**11,660**	**13,712**	**15,927**	**17,295**	**18,444**	**19,689**
Upper 95%-CI	6,054	10,556	13,412	16,266	20,093	23,092	26,224	30,615
Elm Fork Trinity River near Lewisville, Tex.								
Lower 95%-CI	2,811	5,479	7,208	8,947	11,272	13,035	14,789	17,083
Estimate	**3,532**	**6,314**	**8,482**	**10,776**	**14,043**	**16,709**	**19,553**	**23,598**
Upper 95%-CI	4,032	7,476	10,425	13,943	19,886	25,765	33,281	46,621
Elm Fork Trinity River near Carrollton, Tex.								
Lower 95%-CI	4,971	7,535	9,974	12,590	16,362	19,532	23,018	28,175
Estimate	**5,437**	**8,695**	**11,794**	**15,673**	**22,384**	**29,018**	**37,381**	**51,854**
Upper 95%-CI	6,136	10,309	15,011	22,499	40,856	66,619	111,159	224,406
Trinity River at Dallas, Tex.								
Lower 95%-CI	14,617	26,604	35,543	44,368	55,473	63,347	70,779	79,984
Estimate	**16,993**	**30,901**	**41,707**	**53,082**	**69,154**	**82,157**	**95,918**	**115,307**
Upper 95%-CI	19,746	36,345	51,007	68,816	97,782	124,412	155,879	206,351
East Fork Trinity River near Crandall, Tex.								
Lower 95%-CI	6,030	11,463	15,334	19,145	24,008	27,507	30,836	34,975
Estimate	**7,188**	**13,393**	**18,144**	**23,060**	**29,855**	**35,226**	**40,795**	**48,452**
Upper 95%-CI	8,378	15,921	22,239	29,497	41,086	51,788	64,561	85,353
Trinity River near Rosser, Tex.								
Lower 95%-CI	18,529	33,019	43,889	54,770	68,928	79,379	89,599	102,771
Estimate	**21,383**	**38,210**	**51,483**	**65,678**	**86,136**	**103,028**	**121,230**	**147,424**
Upper 95%-CI	24,672	44,881	62,984	85,300	122,635	157,927	200,554	270,595
Trinity River at Trinidad, Tex.								
Lower 95%-CI	20,191	36,137	47,526	58,266	70,819	79,059	86,374	94,866
Estimate	**23,446**	**41,775**	**55,349**	**69,107**	**87,750**	**102,242**	**117,078**	**137,208**
Upper 95%-CI	27,215	48,602	66,407	86,975	118,533	146,186	177,673	226,156

Station number and name and stramflow estimate type	Flood flow frequency by annual exceedence probability (AEP)							
	AEP 0.500 (ft^3/s)	AEP 0.200 (ft^3/s)	AEP 0.100 (ft^3/s)	AEP 0.050 (ft^3/s)	AEP 0.020 (ft^3/s)	AEP 0.010 (ft^3/s)	AEP 0.005 (ft^3/s)	AEP 0.002 (ft^3/s)
Richland Creek near Richland, Tex.								
Lower 95%-CI	9,914	18,328	24,300	30,064	37,152	41,990	46,373	51,534
Estimate	**11,664**	**21,369**	**28,519**	**35,695**	**45,283**	**52,620**	**60,024**	**69,896**
Upper 95%-CI	13,624	25,122	34,342	45,223	63,329	80,320	100,668	133,903
Chambers Creek near Rice, Tex.								
Lower 95%-CI	9,322	17,033	22,451	27,559	33,559	37,462	40,875	44,757
Estimate	**10,929**	**19,786**	**26,158**	**32,434**	**40,649**	**46,815**	**52,936**	**60,951**
Upper 95%-CI	12,756	23,119	31,230	40,544	55,208	68,281	83,369	107,038
Richland Creek near Fairfield, Tex.								
Lower 95%-CI	4,169	11,921	17,607	23,102	29,515	33,519	36,814	40,253
Estimate	**5,943**	**14,951**	**21,995**	**28,907**	**37,565**	**43,636**	**49,249**	**55,947**
Upper 95%-CI	7,584	18,883	28,315	38,571	53,285	65,387	78,668	98,569
Trinity River near Oakwood, Tex.								
Lower 95%-CI	22,280	41,710	56,274	70,550	88,243	100,574	112,048	126,037
Estimate	**26,113**	**48,764**	**66,501**	**85,210**	**111,642**	**132,991**	**155,534**	**187,185**
Upper 95%-CI	30,588	57,624	81,386	109,958	156,099	198,391	248,269	328,070
Trinity River near Midway, Tex.								
Lower 95%-CI	22,458	41,385	54,936	67,652	82,295	91,693	99,868	109,136
Estimate	**26,345**	**48,112**	**64,062**	**80,000**	**101,198**	**117,350**	**133,589**	**155,156**
Upper 95%-CI	30,838	56,248	77,027	101,114	138,190	170,687	207,744	264,984
Trinity River at Riverside, Tex.								
Lower 95%-CI	28,953	49,094	62,152	73,757	86,361	93,935	100,174	106,848
Estimate	**33,370**	**55,929**	**70,789**	**84,555**	**101,480**	**113,474**	**124,849**	**139,016**
Upper 95%-CI	38,296	63,762	81,934	101,614	130,317	154,186	180,309	218,974
Trinity River at Romayor, Tex.								
Lower 95%-CI	33,745	47,707	55,696	63,077	72,196	78,692	84,889	92,680
Estimate	**37,473**	**51,637**	**61,074**	**70,164**	**82,035**	**91,054**	**100,180**	**112,482**
Upper 95%-CI	40,344	56,799	68,707	81,628	101,764	120,289	142,448	178,655

9 Reservoir Studies

9.1 INTRODUCTION TO STAGE FREQUENCY ANALYSIS

This section describes the methods used to update the pool frequency curves for the Trinity River Basin Reservoir projects. The reservoir projects that have been analyzed for this report are Bardwell, Benbrook, Grapevine, Joe Pool, Lavon, Lewisville, Navarro Mills, Ray Roberts, and Richland-Chambers. Richland-Chambers is operated by the Tarrant Regional Water District (TRWD) while the other projects are operated by the United States Army Corps of Engineers (USACE). The frequency curves were developed to represent the current reservoir control plan and watershed conditions (as of 2016). A frequency analysis is a statistical method of prediction that consists of studying past events that are characteristic of a particular hydrology process in order to determine the probabilities of occurrence of these events in the future. A Stage-Frequency curve estimates the annual exceedance probability (AEP) for reservoir pool elevations. For example, if a reservoir pool at the spillway crest has an AEP of 1/50 (1 in 50 years on average), then the reservoir has a 2% chance of the reservoir pool elevation equaling or exceeding the spillway crest elevation in any given year. The stage-frequency curve can be determined using empirical (observed or measured) data; however, the reservoir pool elevations associated with 1% AEP (100-year) or 0.2% AEP (500-year) occurrences are typically beyond the observed reservoir pool elevation period of record (POR). Models serve the purpose of extrapolating reservoir pool elevation frequencies beyond the observed record.

For the presented study, the stage frequency curves representing current conditions were developed to evaluate the Trinity River Basin projects' pools elevations resulting from the 50% AEP (2-year) to the 0.2% AEP (500-year) events. This study incorporates available reservoir inflow and pool data (from historical peaks to the year 2016) into statistical software, and applies statistical methods to estimate the n-day critical inflow duration and simulate inflow and elevation period of record for each reservoir project. The historical peaks may be observed and recorded by local residents or seen as water marks on bridge piers or tree trunks; those water elevation marks can be translated into peak discharge values via the use of models or by extrapolating rating curves or extrapolation of observed data points. For each project, the Hydrologic Engineering Center-Statistical Software Package (HEC-SSP) was used to compute volume duration frequency curves from the annual maximum peak reservoir inflows (Version 2.1.1; USACE, 2017). An empirical stage frequency curve was developed from the available reservoir pool Annual Maximum Series (AMS). An event based stochastic Monte Carlo simulation model, Risk Management Center-Reservoir Frequency Analysis (RMC-RFA), was used to extrapolate the stage frequency curve beyond the limits of the empirical stage frequency curve (Version 1.0.0; USACE, 2017). RiverWare was used to develop a current condition POR for reservoir inflows and elevations (Version 7.1; University of Colorado Boulder, 2017). The AMS results derived from RiverWare were used to create the empirical stage-frequency curve. The empirical stage-frequency curve was used to validate RFA model simulation results. The results showed adequate validation to the upper end of the empirical stage frequency curves and it is believed to be a reasonable extrapolation for frequency of rare pool events.

9.2 METHODS

9.2.1 Empirical Stage-Frequency

For the evaluation of hydrologic loading, an extreme-value series of annual maximum stages needs to be generated from the observed and/or simulated period of record. An empirical stage-frequency curve will then be constructed by ranking the annual maximum data, assigning the data a plotting position, and then plotting the data on probability paper using a plotting position formula. Many plotting position formulas can be used for the orientation of an empirical frequency curve, but a plotting position formula that is flexible and makes the fewest assumptions is preferred (USACE, 2017). Gumbel (1958) summarizes five conditions that a plotting position formula should satisfy:

1. The plotting position must be such that all observations can be plotted
2. The plotting position should lie between the observed frequencies of (m-1)/n and m/n where m is the rank of the observations beginning with m = 1 for the largest value and n is the number of years of record or the number of observations
3. The return period of a value equal to or larger than the largest observation and the return period of a value equal to or smaller than the smallest observation should converge toward n
4. The observations should be equally spaced on the frequency scale
5. The plotting position should have an intuitive meaning, be analytically simple, and easy to use.

The most practical plotting position formula which satisfies all five of Gumble's conditions is the Weibull plotting position. A rank-order method is used to plot the annual maxima. This involves ordering the data from the largest event to the smallest event, assigning a rank of 1 to the largest event and a rank of n to the smallest event, and using rank (i) of the event to obtain a probability plotting position. The Weibull plotting position formula is an unbiased estimator of exceedance probability for all distributions, and is used to plot the stage data for constructing an empirical stage-frequency curve: $P_i = i \,/\, (n + 1)$; where, i is the rank of the event, n is the sample size in years, and P_i is the exceedance probability for an event with rank i.

9.2.2 Volume-Sampling Approach

A common method for estimating a hydrologic loading curve for a dam is by volume-based sampling. In this method, a large number of flood events is generated using random sampling of flood volumes, the associated flood hydrographs are routed through the reservoir, and the peak reservoir elevation for each event is recorded.

The general workflow for a volume-based hydrologic loading analysis is as follows:

1. Choose a stage for the reservoir to begin the flood event
2. Choose an inflow flood hydrograph to scale
3. Sample a flood volume from the reservoir inflow frequency curve
4. Scale the selected flood hydrograph to match the sampled flood volume
5. Route the scaled flood hydrograph through the reservoir using an operations model
6. Record the peak stage that occurred during the event.

For the stochastic model, RMC-RFA, choices made in steps 1-3 are made using random selection from a probability distribution. The choice is random in the sense that it occurs without pattern, but the relative frequency of the outcomes in the long term is defined by a probability distribution. Reservoir stages for starting the simulation come from a *pool duration curve*, which is a probability distribution for the elevation of the reservoir pool. They may be seasonally-based, in which case first the season of the flood event occurrence is selected at random, and then a starting stage is selected at random from the pool duration curve for that particular season. Sampled flood volumes come from the familiar flow frequency curve produced by fitting an analytical probability distribution to an AMS of river discharges. In the volume-based approach, instead of analyzing instantaneous peak discharge (as is typically the case in a Bulletin 17B/C-type analysis), the analysis is performed on a longer-duration volume (such as three or four day average discharge.)

When steps 1-6 are performed a large number of times (for example, 10,000 *samples*), the resulting peak stages are ranked and plotted, producing a stage-frequency curve for the reservoir. However, substantial uncertainty exists in several of the inputs to the model, especially the inflow frequency curve. To account for these uncertainties, steps 1-6 are performed a large number of times with different parameters for the inputs. The input parameters are varied across *realizations*, and for each realization, steps 1-6 are repeated over a large number of *samples.* Thus, the full simulation with uncertainty will contain a number of events equal to the number of realizations times the number of samples. By varying parameters across realizations, the uncertainty in the probability of an event, for example reaching spillway crest elevation, can be better assessed. Each realization will produce an estimate of the probability of reaching this elevation based on the parameters used to drive the realization. Percentiles (for example the 5th and 95th percentiles) of these probabilities produce a confidence interval for the probability of reaching the spillway. If the mean probability of exceeding any stage is taken, then the result is the *expected frequency curve*, which is the single best estimate for the probability of exceeding a particular stage.

9.2.3 Risk Management Center - Reservoir Frequency Analysis (RMC-RFA)

RMC-RFA software was developed by the USACE Risk Management Center for use in dam safety risk assessments. It can produce a stage-frequency curve with confidence bounds using a stochastic model with the volume-sampling approach. The model functions best in situations where dam operations are relatively simple, especially when the spillway is not regulated using gates. A simplification of the operational rules is assumed through the use of an elevation-discharge table which is based on a combination of dam discharge structures and calibration to historical releases. Development of model inputs is aided by tools within the program that allow the user to estimate inputs, such as flood seasonality or pool duration curves, in a consistent and automated manner. Other inputs, such as the volume frequency curve or reservoir operations, are developed by the user independently.

9.3 DATA ANALYSIS AND MODEL INPUT

9.3.1 Inflow Hydrograph and Pool Stage

Estimates of daily average flows and pool elevations for the Trinity River Basin projects were retrieved from the USACE water management database system for water year (WY) 1925 through WY 2016 for Joe Pool and Lavon Lakes; and for WY 1941 through WY 2016 for Bardwell, Benbrook, Grapevine, Lewisville, Navarro Mills, Ray Roberts, and Richland-Chambers Lakes. Records prior to project construction were simulated using RiverWare. Joe Pool and Lavon Lakes were extended further than the rest of the projects due to available USGS discharge data, which covers longer periods. The Trinity River Basin project impoundment dates are shown in Table 9.1. RiverWare software mimics a watershed by modeling its features as linked objects, including storage or power reservoir objects, stream reach objects, groundwater storage objects, or diversion objects. In a simple model, these objects simulate basic hydrologic processes through mass balance calculations and can be linked to one another through inflow-outflow calculations. More advanced modeling is achieved by selecting object-specific methods that further define the hydrologic processes associated with each object. Additionally, RiverWare may operate under a rule-based simulation, which creates logic-based interdependency of objects through user-defined rules. These rules may look forwards and backwards in time, and given priorities in one rule may supersede others depending on the importance defined by the user. These detailed yet simple modeling techniques allow RiverWare to simulate reservoir pool elevations and inflows efficiently.

Table 9.1: Trinity River Basin Dams Deliberate Impoundment Dates

Project	Bardwell	Benbrook	Grapevine	Joe Pool	Lavon
Impoundment Date	20 Nov 1965	29 Sep 1952	3 Jul 1952	7 Jan 1986	14 Sep 1953
Project	Lewisville	Navarro Mills	Ray Roberts	Richland-Chambers	
Impoundment Date	01 Nov 1954	15 Mar 1963	30 Jun 1987	14 Jul 1987	

The USACE water management section inspected the dataset for quality before being used in the analyses. The instantaneous (hourly) lake inflows were gathered. One example is the Bardwell Lake hourly inflow shown in Figure 9.1. The hourly records may contain many gaps. The gaps are for times when real time recording was missing. Data with missing records were not used in the analyses. In this report, Grapevine Lake was used to illustrate the simulated pre-dam construction daily average inflow and post dam construction pool elevation records; see Figure 9.2. All project inflows and pool elevations can be presented in a similar manner.

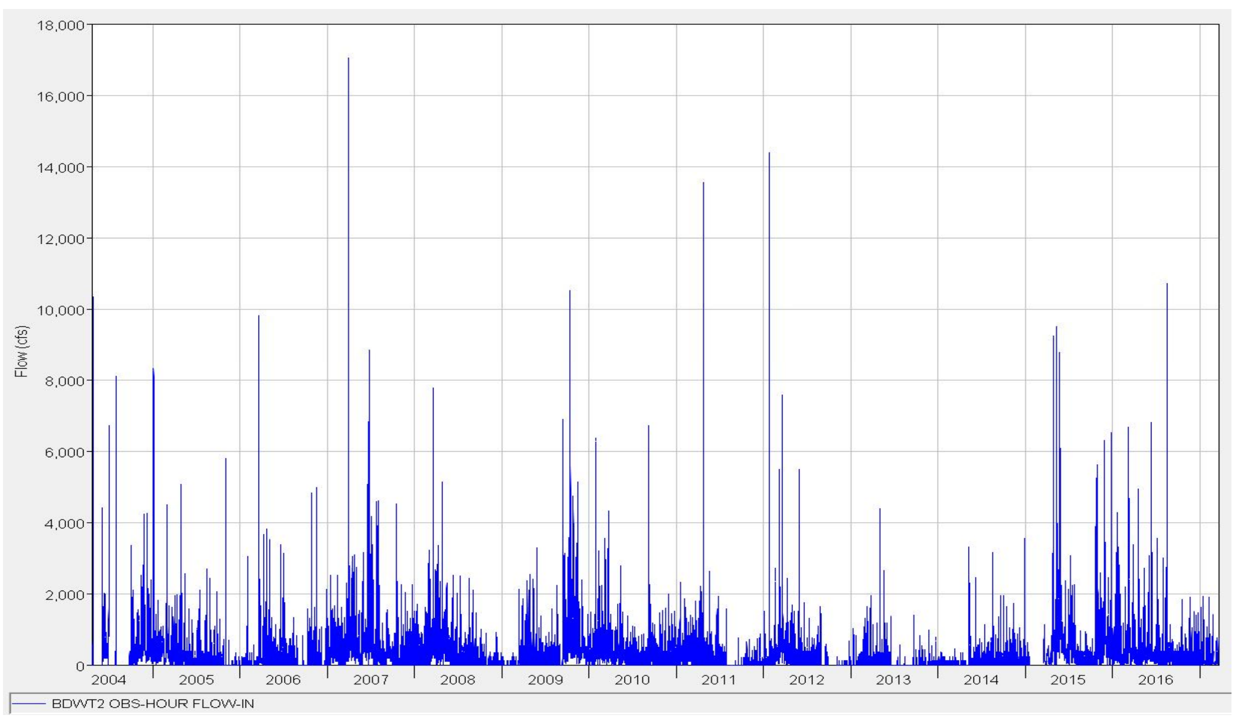


Figure 9.1: Bardwell Lake Hourly Inflow

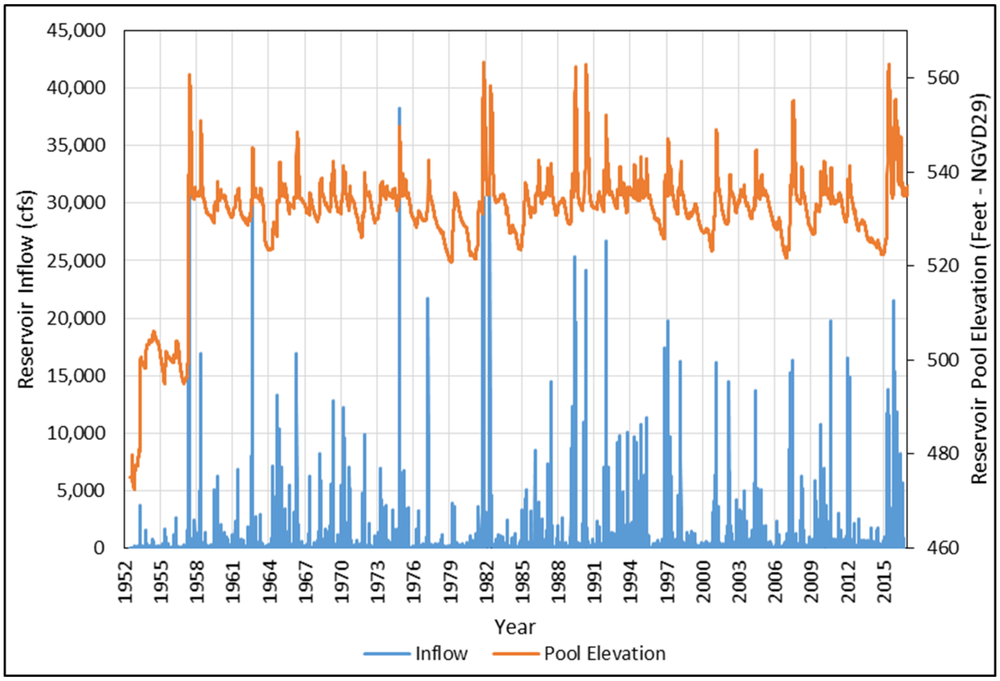


Figure 9.2: Grapevine Lake Daily Average Inflow and Elevation

9.3.2 Instantaneous Peak Estimates

An extract of the 1-day average maximum annual peaks for each project was made available for the analysis. The lake inflow systematic record contains a mixed population of observed (recorded) post-dam construction flows and pre-dam construction synthetic flow years generated using RiverWare. The unrecorded historical n-day peaks at the lakes were developed by establishing a discharge peak correlation with the nearest USGS gage when available. The USGS gages used for correlation are listed in Table 9.2. The criteria of selection was based on each gage location, its proximity to the corresponding lake, and its drainage area size in relation to the reservoir contributing drainage area. In addition, the observed hydrographs entering the reservoir must mimic similar patterns of those observed at the gage location to be considered. Historical peaks at the selected USGS gages were generated by establishing a relationship between stage where historical high water marks were captured and discharge peaks. Once a strong trendline correlation was maintained with a high R^2 value, the corresponding regression equation was used to estimate the peak. A stage-peak relationship example is illustrated in Figure 9.3. Table 9.2 lists the historical peaks estimated from the rating curves at each USGS gage. No USGS gage or historical peaks are associated with Richland Chambers Lake.

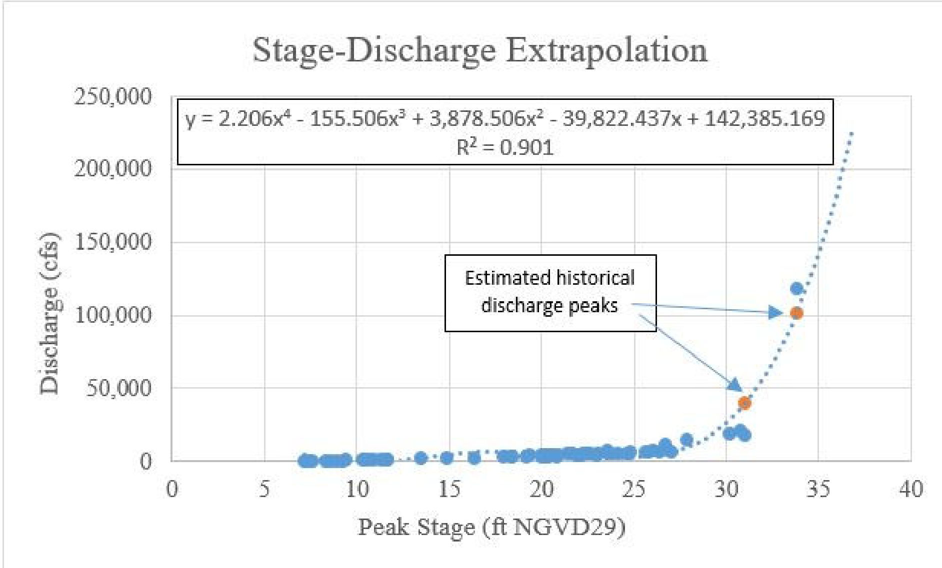


Figure 9.3: Stage-Discharge Corresponding Relationship for USGS 08053000 Elm Fk Trinity River near Lewisville.

Table 9.2: Trinity River Basin USGS Estimated Historical Peaks

Historical Year	Bardwell USGS ID # 8064500 Peak (cfs)	Historical Year	Benbrook USGS ID # 8046000 Peak (cfs)	Historical Year	Grapevine USGS ID # 8054000 Peak (cfs)	Historical Year	Joe Pool USGS ID # 8050100 Peak (cfs)
1887	68,488	1922	67,970	1908	55,700	1922	67,186
1913	41,155						
1936	24,176						
Historical Year	**Lavon USGS ID # 8061500 Peak (cfs)**	**Historical Year**	**Lewisville USGS ID # 8053000 Peak (cfs)**	**Historical Year**	**Navarro Mills USGS ID # 8063100 Peak (cfs)**	**Historical Year**	**Ray Roberts USGS ID # 8050500 Peak (cfs)**
1908	13,386	1908	118,615	1929	52,400	1908	103,014
1913	32,957						
1922	65,601						
1924	67,257						

9.3.3 Daily Average Annual Peak Estimates

The reservoir projects' historical n-day inflows were generated from the USGS gages historical peaks. Several attempts were made to better justify the best predictable peaks. The drainage area to peak ratio method was applied to calculate the projects' inflow peaks. The method was found applicable for the Trinity River Watershed streams. The predicted peaks follow a general straight line trend which is used to estimate the peaks. The trendline interpolates between peaks. It produces the best formula used for prediction. The 5% and 95% confidence bounds can be generated using the formula:

$X = Y \pm t_{\alpha} * SE^{(1/n + [(X\text{-}Xm)2]/SSxx)}$; where X is the instantaneous AMS peak, Y is the predicted n-day daily average AMS, t_{α} represents the two-tailed inverse distribution for the 5% and 95% probabilities (confidence bounds), SE is the standard error, n is the number of years, X_m is the average instantaneous peak value, and SS_{xx} is the sum of squares of deviations of data from their sample mean ($\sum(X\text{-}X')^2$). An example of a correlation between the instantaneous peaks and the 1-Day AMS peaks with the predicted value for Lavon Lake is illustrated in Figure 9.4.

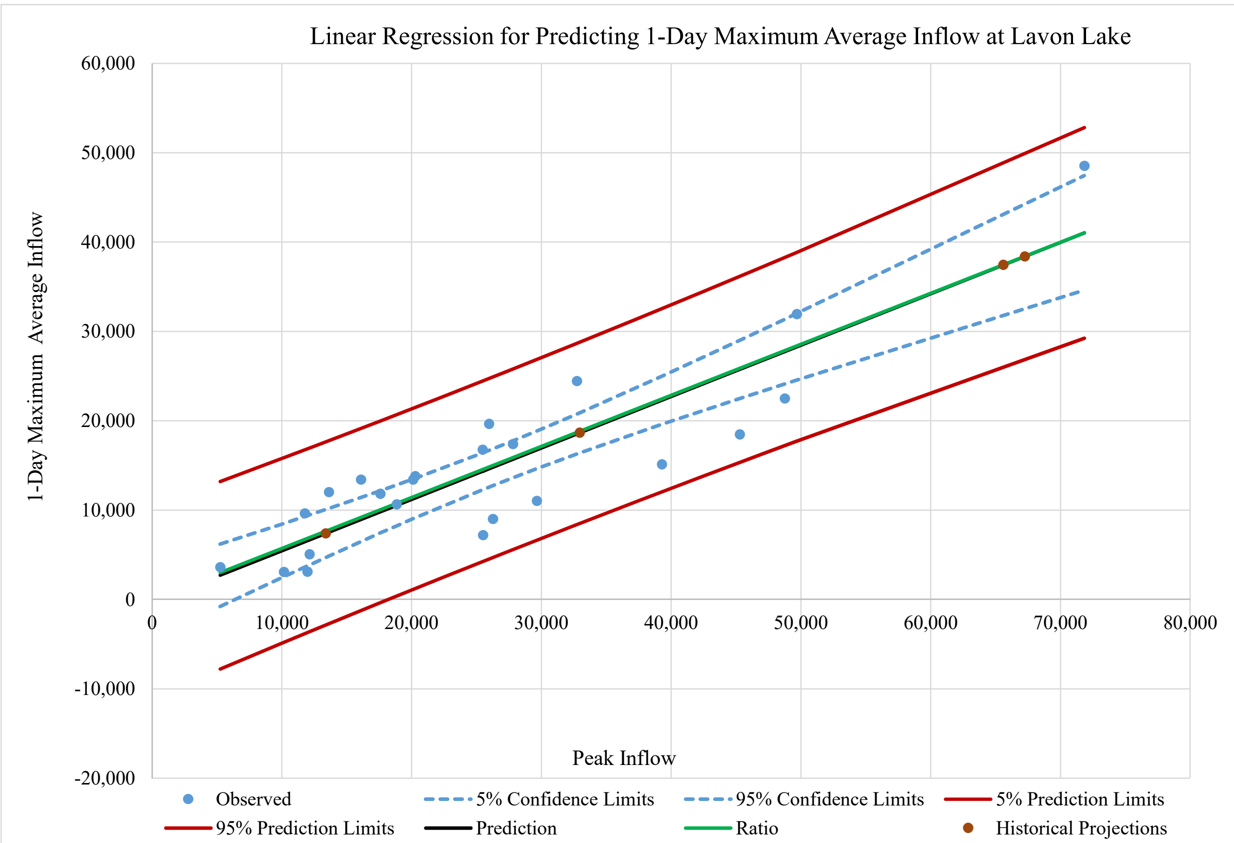


Figure 9.4: Lavon Lake 1-Day AMS Best Estimate

Furthermore, peak results obtained from the drainage area to peak ratio method were validated by analyzing the peaks and applying best fitting curves through the instantaneous- n-day AMS data points. The n-day AMS historical peaks can be estimated by utilizing the best corresponding relationship (formula) with the strongest R^2 value among all fitting curves. Figure 9.5 illustrates the corresponding correlation that best depicts the missing historical peaks for Joe Pool. The 1-day AMS best estimated peak was 15,980cfs, which compares closely to the best estimated peak from applying the drainage area to peak ratio method at 15,350cfs. In this report, peaks estimated from the drainage area to peak ratio method with 5% and 95% confidence bounds were adopted in the study and used for further analyses for all USACE projects.

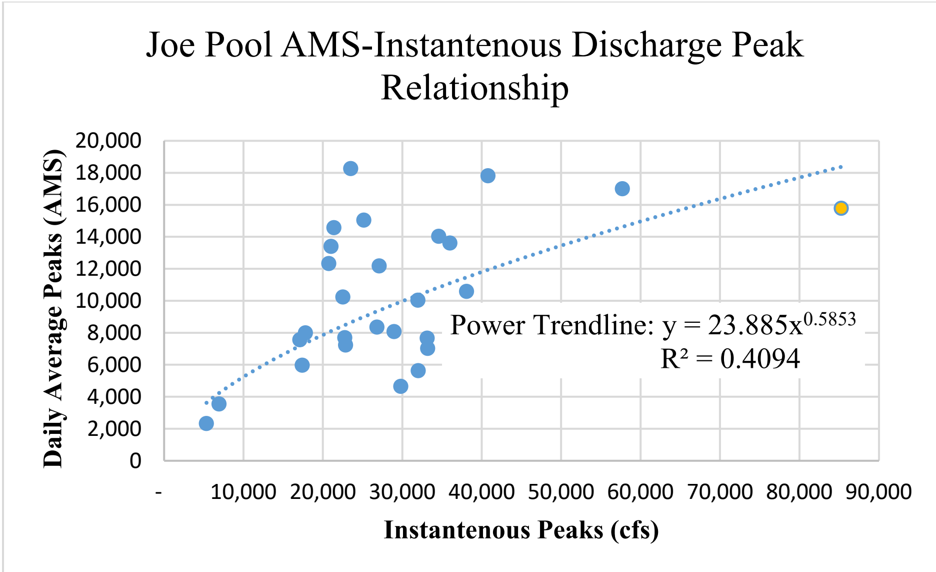


Figure 9.5: Joe Pool Inflow Discharge Relationship

Table 9.3 is a summary of each project's instantaneous peak and the developed 2, 3, 4, and 5-day AMS historical peaks, which can be generated similarly to the 1-day AMS peaks shown in Figure 9.4.

Table 9.3: Trinity River Basin N-Day AMS Estimated Historical Peaks

Project	N-Day Duration AMS Peak (cfs) (Historical)						Instantenous Peak (cfs)
	Year	1-Day	2-Day	3-Day	4-Day	5-Day	
Bardwell	1887	12,504	11,040	8,067	6,479	5,348	29,659
	1913	6,477	5,446	4,075	3,313	2,771	14,350
	1936	3,894	3,048	2,364	1,956	1,667	7,789
Benbrook	1922	49,570	30,921	22,706	19,266	13,847	67,970
Grapevine	1908	24,082	21,161	18,127	15,299	13,214	55,700
Joe Pool	1922	15,347	12,582	10,034	8,674	7,730	67,186
Lavon	1908	7,390	6,633	5,677	5,000	4,477	13,386
	1913	18,651	15,982	13,638	11,829	10,342	32,957
	1922	37,436	31,577	26,917	23,221	20,124	65,601
	1924	38,390	32,368	27,591	23,799	20,620	67,257
Lewisville	1908	96,998	72,608	54,507	43,060	35,462	118,615
Navaro Mills	1929	30,322	19,047	13,680	10,584	8,724	52,400
Ray Roberts	1908	51,939	33,518	25,654	21,105	18,153	103,014
Richland Chambers	None	N/A	N/A	N/A	N/A	N/A	N/A

9.4 CRITICAL INFLOW DURATION ANALYSIS

The critical inflow duration can be defined as the inflow duration that tends to produce most consistently the highest water surface elevation for the reservoir. Although projects located on the Trinity River Basin are impacted by similar weather patterns and storms usually occur in similar seasons, it is very likely projects will have different critical durations due to the fact that each project's sub-watershed is featured by a unique contributing drainage area and topography. Steep slopes result in rapid runoff (short critical duration), and flatter slopes result in a longer critical duration. The storm duration can also impact critical durations; longer storms result in longer critical durations. For these nine dams in the Trinity River Basin, the most critical flood season was determined to occur during the spring, between March and June. In order to determine critical inflow duration of the observed rainfall-runoff events, extreme rainfall runoff (inflow) events are examined. All large inflow events are independent, meaning that different year hydrographs can be presented in one figure to determine the proper critical duration. The duration peak inflow was used to determine a reasonable value for critical inflow duration. Although this method was found accurate to produce good estimates, the critical duration can be adjusted later on during the analysis to reflect the most appropriate frequency curve. Best engineering judgment remains necessary in the final selection of the most appropriate value. For each project, a set of historical inflow events (hydrographs) with daily peak inflows greater than a certain threshold were extracted from the RiverWare simulated daily average inflow period of record (*i.e.* examine the top 20% largest independent inflow events for each project inflow). The best estimate inflow duration for the reservoir is estimated by taking the average hydrograph of the major events specified. Bardwell Lake was selected to demonstrate the lake inflow critical duration best estimate (Figure 9.6).

Best estimates of the n-day critical durations for all projects are listed in Table 9.4. These results were finalized after making several sensitivity analyses while running the RMC-RFA program. The best critical duration estimate produced the most conservative frequency elevation in the lake. The purpose of this analysis is to have a better understanding of the runoff response from large single rain events that helps establish what volume discharge frequency curves need to be examined.

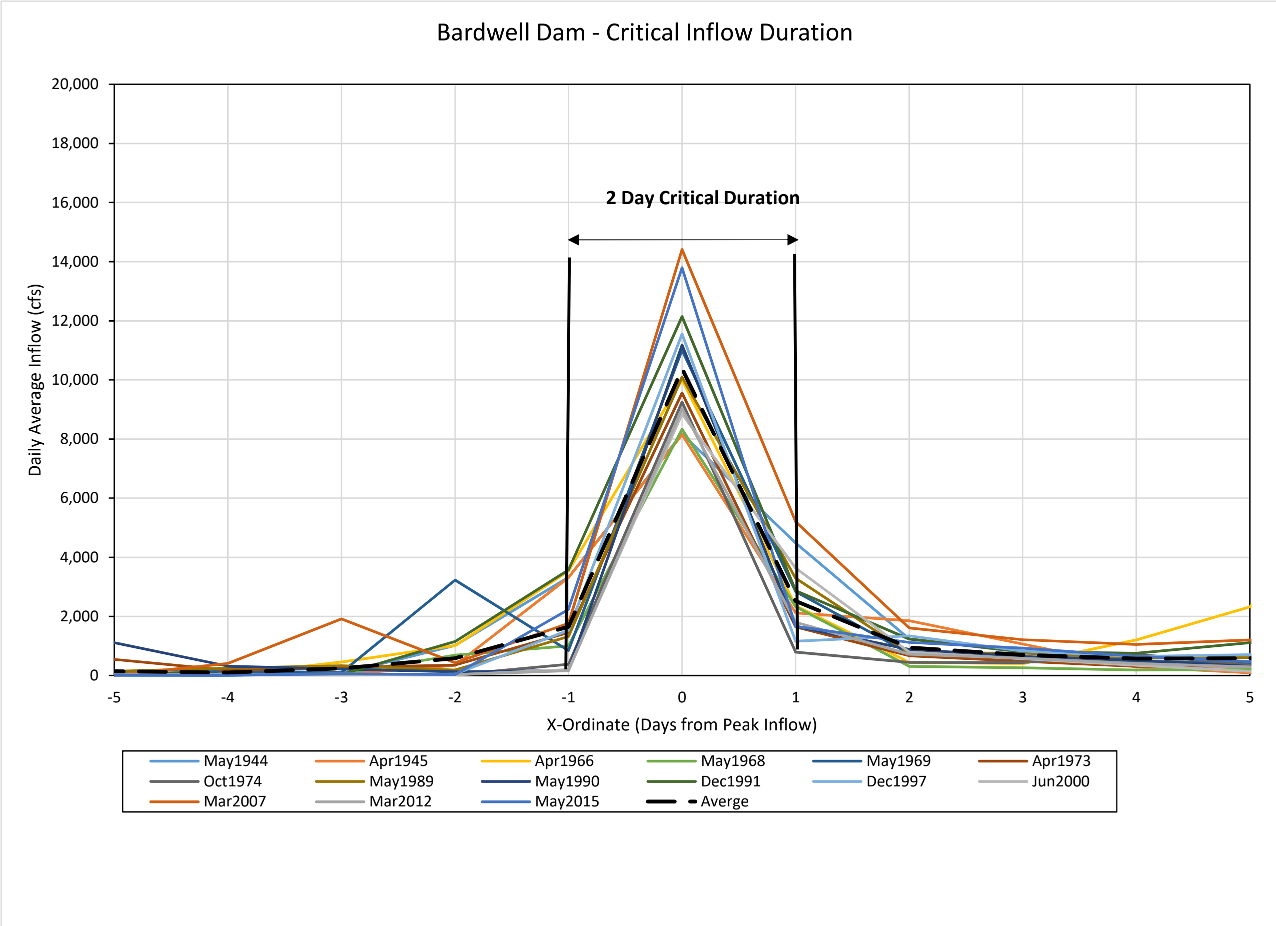


Figure 9.6: Bardwell Lake Critical Duration Inflow Analysis

Table 9.4: Trinity River Basin Inflow Duration Analysis

Project	Minimum Threshold Peak (cfs)	Number of Analyzed Inflow Events	Critical Duration (Days)
Bardwell	8,000	15	2
Benbrook	11,000	13	2
Grapevine	19,500	13	3
Joe Pool	3,200	16	2
Lavon	30,400	12	3
Lewisville	43,000	14	3
Navarro Mills	18,000	12	2
Ray Roberts	34,800	12	2
Richland Chambers	40,000	10	3

9.4.1 Volume/Flow Frequency Statistical Analysis

The volume/flow frequency analyses for the Trinity River Basin lakes were estimated by following Bulletin 17C guidelines and procedures (statistical techniques) to determine exceedance probabilities associated with specific flow rates utilizing HEC-SSP (Version 2.1.1; USACE, 2017). The observed and developed daily average annual maximum peaks were used to establish a relationship between flow magnitude and frequency. In this report, the term volume/flow frequency refers to the frequency with which a flow over a given duration, such as 1-, 2-, 3-, 4-, and 5-day, is expected to be equaled or exceeded. The duration range selection was based on inspecting the shape of the hydrographs such as those shown in Figure 9.6 and the critical durations listed in Table 9.4. To adequately assess the risk associated with the Trinity River Basin Dams' structures in question, the 2-Day critical duration was used to construct hypothetical inflow frequency events for Bardwell, Benbrook, and Joe Pool; the 3-Day critical duration was used to construct inflow frequency events for Grapevine, Lavon, Lewisville, Navarro Mills, Ray Roberts, and Richland Chambers dams. The events were routed through the projects to estimate the reservoirs' stage-frequency curves.

9.4.2 Bulletin 17C

The use of Bulletin 17C guidance allows for computations of the annual exceedance probability of the instantaneous and daily average peaks, using the Expected Moments Algorithm (EMA). It estimates distribution parameters based on sample moment in a more integrated manner that incorporates non-standard, censored, or historical data at once, rather than as a series of adjustment procedures (Cohn et al., 1997). In this report, and when applicable, each project was assigned the associated historical peaks shown in Table 9.3 (*i.e.* Ray Roberts, for a 2-day critical duration would be assigned one (1) historical peak of 33,518cfs for the year of 1908). Values of perception thresholds from the historical peak events were set for the historical peak years for each project (*i.e.* 1908 was set for Ray Roberts). The set of threshold peaks define the range of stream flow for which a flood event could have been observed; consequently, years for which an event was not observed and recorded must have had a peak flow rate outside of the perception threshold. The use of Bulletin 17C procedures provide confidence intervals for the resulting frequency curve that incorporate diverse information appropriately, as historical data and censored values impact the uncertainty in the estimated frequency curve (Cohn et al., 2001). Within the Bulletin 17C EMA methodology, every annual peak flow in the analysis period, whether observed or not, is represented by a flow range that might simply be limited to the gaged value when one exists. However, it could also reflect an uncertain flow estimate which is the case for the Trinity River Basin projects.

9.4.3 HEC-SSP Calculations

A series of n-day volume duration frequency curves was developed for each of the Trinity River Basin projects. The volume duration frequency results from this analysis were developed using HEC-SSP. The Multiple Grubbs-Beck Test (MGBT) algorithm was used for the low outlier test. Plotting position of the censored data is adopted from the Hirsch-Stedinger plotting position algorithm (Hirsch, 1982). Except for assigning only a station skew value to Richland Chambers, a regional skew value was made available and incorporated to the study as part of the analysis to calculate the generalized skew in addition to computations made using the systematic (observed) station skew value. More details about the regional skew development and Mean Squared Error (MSE) value can be found in the "Model Comparison for Regional Skew Analysis for Trinity River Basin USACE Reservoirs in Texas" report (USACE Fort Worth District, 2017). HEC-SSP gives the option to analyze data with different skew values to best estimate the stage frequency curve. Each developed frequency curve underwent different analysis techniques before adoption. The MSE value of 0.141 was used. Table 9.5 contains skews and record lengths for each project input into the HEC-SSP program.

Table 9.5: Summary of HEC-SSP Input Parameters

Project	Systematic Record (years)	Historic Record (years)	Regional Skew	MSE
Bardwell	77	137	-0.52	0.141
Benbrook	77	159	-0.52	0.141
Grapevine	76	109	-0.52	0.141
Joe Pool	92	95	-0.52	0.141
Lavon	92	109	-0.52	0.141
Lewisville	76	109	-0.52	0.141
Navarro Mills	78	122	-0.52	0.141
Ray Roberts	76	117	-0.52	0.141
			Station Skew	
Richland Chambers	76	76	-0.282	N/A

Note: The actual systematic record length is less than the systematic record length shown in the Table. The actual systematic record length was extended utilizing RiverWare.

The computed frequency flows from HEC-SSP for the different Trinity Basin reservoirs are listed in Table 9.6. The statistical parameters generated based on applying the Bulletin17C EMA method, regional skews and MSE, and low outlier tests for Multiple Grubbs-Beck are listed in Table 9.7. Only pertinent critical durations were listed for each project (*i.e.* 2-Day and 3-Day).

Table 9.6: Trinity River Basin Lakes Bulletin 17C Computed Median Inflows

N	ACE	Bulletin 17C EMA Computed Average (Median) Peaks (cfs)								
Yrs	%	Bardwell	Benbrook	Joe Pool	Navarro Mills	Ray Roberts	Grapevine	Lavon	Lewisville	Richland Chambers
		2-Day					3-Day			
500	0.2	10,972	32,421	27,639	28,854	75,364	37,167	50,344	111,664	104,115
200	0.5	9,626	26,362	23,650	25,428	62,457	31,610	44,026	96,437	86,850
100	1	8,586	21,977	20,606	22,720	53,095	27,362	39,122	84,584	74,437
50	2	7,528	17,802	17,553	19,911	44,118	23,103	34,112	72,493	62,588
20	5	6,098	12,670	13,529	16,040	32,899	17,510	27,332	56,249	47,795
10	10	4,987	9,135	10,515	12,987	24,946	13,356	22,073	43,857	37,245
5	20	3,839	5,949	7,542	9,808	17,476	9,317	16,672	31,459	27,191
2	50	2,198	2,360	3,662	5,288	8,286	4,218	9,089	15,082	14,322

Table 9.7: Trinity River Basin Lakes Bulletin 17C Computed Median Inflow Statistics

Statistics	2-Day Computed Statistics					3-Day Computed Statistics			
	Bardwell	Benbrook	Joe Pool	Navarro Mills	Ray Roberts	Grapevine	Lavon	Lewisville	Richland Chambers
Mean	3.32	3.33	3.53	3.69	3.89	3.58	3.93	4.14	4.14
Standard Deviation	0.31	0.52	0.41	0.35	0.41	0.45	0.34	0.42	0.35
Station Skew	-0.29	-0.47	-0.65	-0.94	-0.33	-0.73	-0.5	-1.01	-0.28
Historical Events	3	1	1	1	1	1	4	1	0
Low outliers	29	40	45	28	1	21	14	27	1
Missing Flows	57	66	2	43	40	32	13	32	0
Systematic Events	77	92	92	78	76	76	92	76	76
Effective Recod Length	108	119	50	94	116	88	95	82	76

Note: The number of missing flows capture gaps between historical event peak years and the earliest systematic peak event in the POR

9.5 RMC-RFA DATA INPUT

9.5.1 Inflow Hydrographs

Several inflow hydrographs were selected to route through RMC-RFA. The particular years of which hourly reservoir inflow hydrographs were routed are:

Bardwell: Available inflow hydrographs for March 2017, May 2015 (2 events), and October 2009.
Benbrook: Available inflow hydrographs for March 2007, April 2008, March 2012, and November 2015.
Grapevine: Available inflow hydrographs for June 1941, June 1989, September 2010, and November 2015.
Joe Pool: Available inflow hydrographs for March 2007, September 2009, January 2012, and May 2015.
Lavon: Available inflow hydrographs for May 1982 and May 2015.
Lewisville: Available inflow hydrographs for May 1990, April 2007, June 2007, and May 2015.
Navarro Mills: Available inflow hydrographs for June 2010, March 2012, May 2015, and October 2015.
Ray Roberts: Available inflow hydrographs for June 2007, April 2009, May 2015, and November 2015.
Richland Chambers: Available inflow hydrographs for May 2015 and October 2015.

The selected hydrographs' characteristics represent different hydrograph shapes (from peaky to large volume events) experienced at the Trinity River Basin lakes. Samples of the selected hourly hydrographs for Grapevine Lake are shown in Figure 9.7.

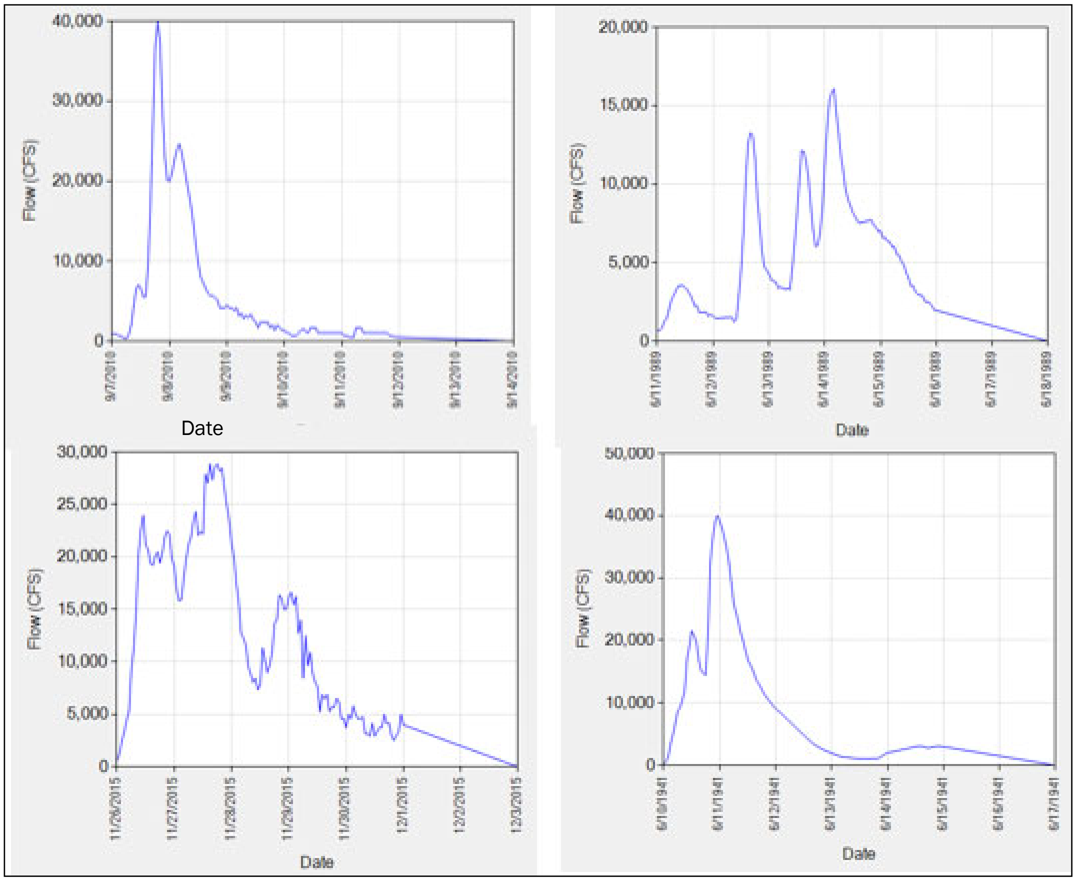


Figure 9.7: Grapevine Lake Inflow Hydrographs

9.5.2 Volume Frequency Curve Computation

The computed volume frequency statistical parameters shown in Table 9.7 were fed into the RMC-RFA program to produce the n-day duration inflows for all projects. As stated in the HEC-SSP computations section, Bulletin 17C procedures and guidelines were followed to produce the volume discharge frequencies. A sample plots of al 2-Day discharge frequency curves is shown in Figure 9.8. The complete list of curves are located in Appendix E – Reservoir Studies.

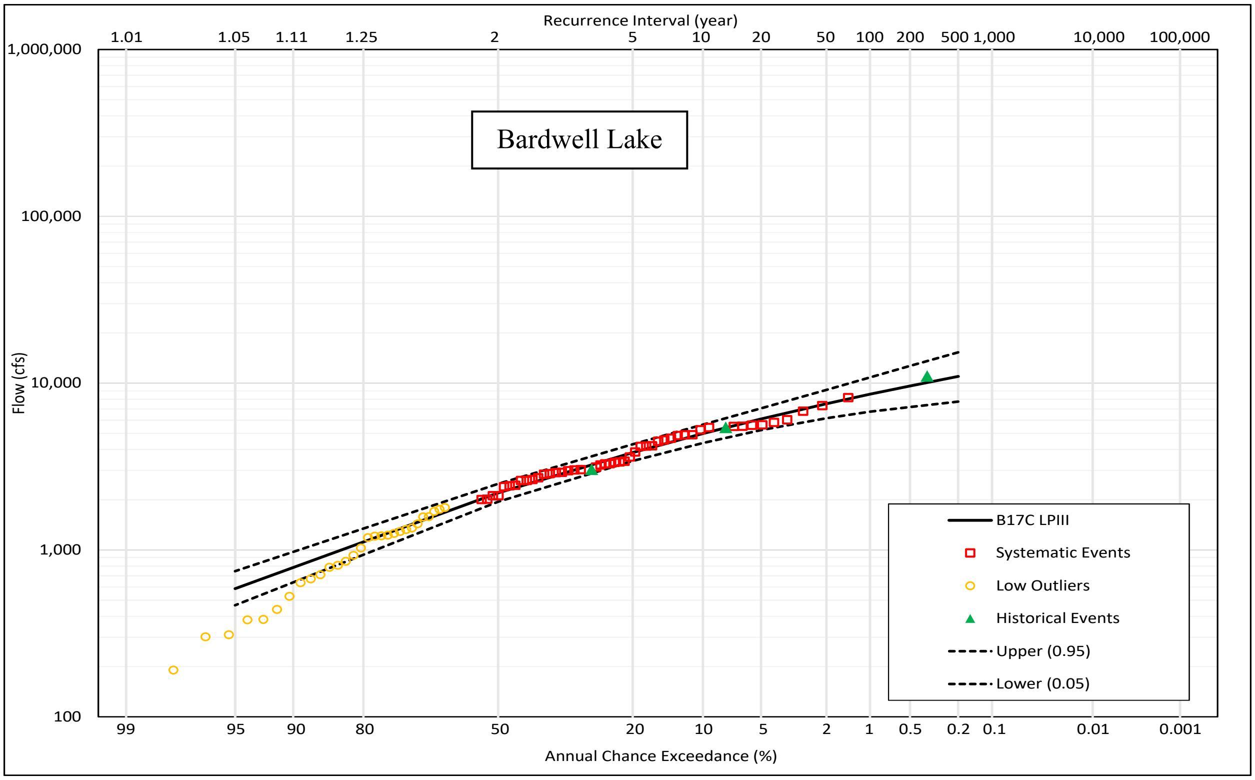


Figure 9.8: Bardwell Lake Computed 2-Day Volume Frequency Curve

9.6 RMC-RFA ANALYSES

9.6.1 Flood Seasonality

Many reservoirs have operations (pool level) that vary by season in response to the cyclical changes in meteorology and hydrology throughout the year. The inflow pattern at the Trinity River Basin lakes have two distinct mechanisms that raise the pool elevation: thunderstorms and tropical storms. Thunderstorms can occur at any time of the year and tropical storms can happen between June and November. Due to meteorological and hydrologic conditions, most significant floods occur during late spring, summer, and fall months.

The term *flood seasonality* is intended to describe the frequency of occurrence of rare floods on a seasonal basis, where a rare flood is defined as any event where the flow exceeds some user specified threshold for a specified flow duration. In the RMC-RFA model operation, a month of flood occurrence is first selected at random according to the relative frequency. Once the month of flood occurrence is specified, a starting pool elevation for the event can be determined from the reservoir stage-duration curve for that particular month. This approach ensures that seasonal variation in reservoir operations is a part of the peak-stage simulation.

The flood seasonality analysis is performed two ways: 1) Assign critical n-day flood seasonality, threshold flow, maximum events per year, and minimum days between events. With these criteria, a total number of events can be calculated. It should be noted that the critical duration used could be different from the volume frequency curve adopted critical duration. 2) Screen out annual maximum peak reservoir pool elevations for the period of record. Peak reservoir pool elevations are the result of significant inflow events and variation of reservoir pool operations. A sensitivity analysis can be done to determine which method applies better when running RMC-RFA; this is done to obtain the most defensible starting pool elevation corresponding to the most frequent events for each month. Projects for which the flood seasonality input parameters were applied (method 1) are listed in Table 9.8. Table 9.9 lists projects where screening for the period of record annual maximum peak performed better (method 2). A list of results obtained by method 1, including Ray Roberts, were also included in Table 9.9.

Table 9.8: Flood Seasonality Parameters Input Method

Project	Critical Duration (Days)	Threshold Flow (cfs)	Minimum Days Between Events	Maximum Number of Events
Ray Roberts	3	10,000	7	5
Richland Chambers	3	20,000	14	1

Table 9.9: Reservoir Stage AMS Peak Analysis and Parameter Input Method Results

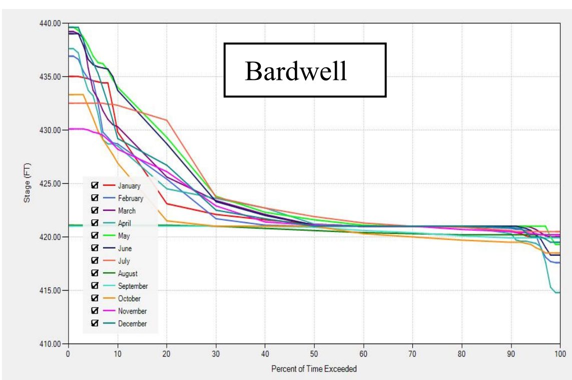
Month	Relative Frequency by Stage AMS (Method 2)							
	Bardwell		Benbrook		Grapevine		Joe Pool	
	Frequency	Relative Frequency	Frequency	Relative Frequency	Frequency	Relative Frequency	Frequency	Relative Frequency
January	4	0.050	0	0.000	0	0.000	2	0.031
February	4	0.050	2	0.030	4	0.050	5	0.061
March	9	0.120	9	0.120	7	0.090	5	0.061
April	8	0.100	4	0.050	4	0.050	8	0.101
May	16	0.210	20	0.260	18	0.230	19	0.251
June	13	0.170	14	0.180	17	0.220	12	0.161
July	2	0.030	3	0.040	4	0.050	4	0.051
August	0	0.000	0	0.000	0	0.000	0	0.000
September	1	0.010	2	0.030	2	0.030	1	0.011
October	7	0.090	15	0.190	12	0.160	16	0.211
November	3	0.040	5	0.060	6	0.080	1	0.011
December	10	0.130	3	0.040	3	0.040	4	0.050
Month	Relative Frequency by Stage AMS (Method 2)						Applying Method 1	
	Lavon		Lewisville		Navarro Mills		Ray Roberts	
	Frequency	Relative Frequency	Frequency	Relative Frequency	Frequency	Relative Frequency	Frequency	Relative Frequency
January	3	0.040	3	0.041	5	0.061	2	0.030
February	2	0.030	1	0.011	3	0.041	4	0.050
March	7	0.090	8	0.101	8	0.101	8	0.100
April	8	0.100	5	0.061	6	0.081	6	0.080
May	19	0.250	16	0.211	19	0.251	12	0.160
June	14	0.180	9	0.121	14	0.181	11	0.140
July	2	0.030	3	0.041	2	0.031	2	0.030
August	0	0.000	1	0.011	1	0.011	0	0.000
September	2	0.030	3	0.041	0	0.000	2	0.030
October	13	0.170	19	0.250	8	0.101	21	0.270
November	4	0.050	5	0.061	3	0.041	4	0.050
December	3	0.030	4	0.050	8	0.100	5	0.060

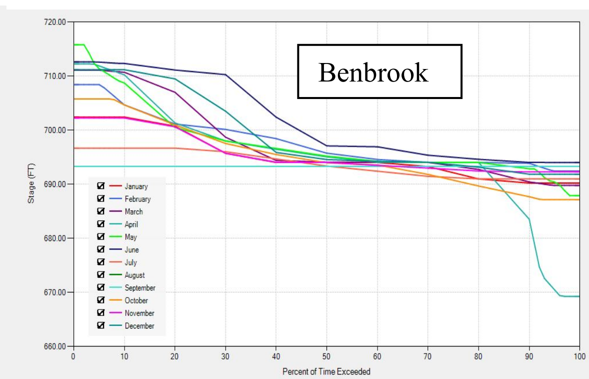
9.6.2 Reservoir Starting Stage Duration

Reservoir starting pool duration curves represent the percent of time during which particular reservoir pools are exceeded. With the exception of Richland-Chambers Lake, an inflow threshold method was used to establish starting pool duration curves based on an inflow threshold value, which is normally selected to meet the value that falls under the estimated n-day critical duration and its most frequent event (volume) value. By doing so, all inflow hydrographs into the lake only consider rising limbs responsible for raising the pool. The projects final duration curves are illustrated in Figure 9.9. The starting pool duration curves showed consistent patterns of pool changes of when pools were exceeded between (40-50) % and 70% of the time for all months. Several starting pool duration curves were generated based on varying the inflow threshold peak values. The finalized inflow threshold peaks along with the final critical durations are listed in Table 9.10. Richland-Chambers reservoir starting stage was estimated by analyzing pool elevations by first filtering observed daily average pools so that they only represent typical starting pools based on a pool change threshold. Then, the filtered data set is sorted by month or season. Because RMC-RFA chooses a starting pool elevation for its simulations based on historic data, the historic data must be filtered so that it is not influenced by flooding events. Starting pool elevations should form the basis for flooding events, not be the result of said events. Therefore, historic pool elevations were filtered with a pool change threshold of 0.5 feet per day and a typical high (flood) pool duration of 12 days. This filtered stage data now forms the basis for the starting pool elevation for the RMC-RFA reservoir simulation. Table 9.11 lists Richland Chambers' filtered starting pool elevations by month and probability.

Table 9.10: Trinity River Basin Threshold Peaks and Critical Durations

Project	Bardwell	Benbrook	Grapevine	Joe Pool	Lavon	Lewisville	Navarro mills	Ray Roberts
Inflow Threshold (cfs)	483	275	447	570	2,100	2,400	1,100	1,250
critical Duration (Days)	2	2	3	2	3	3	2	2





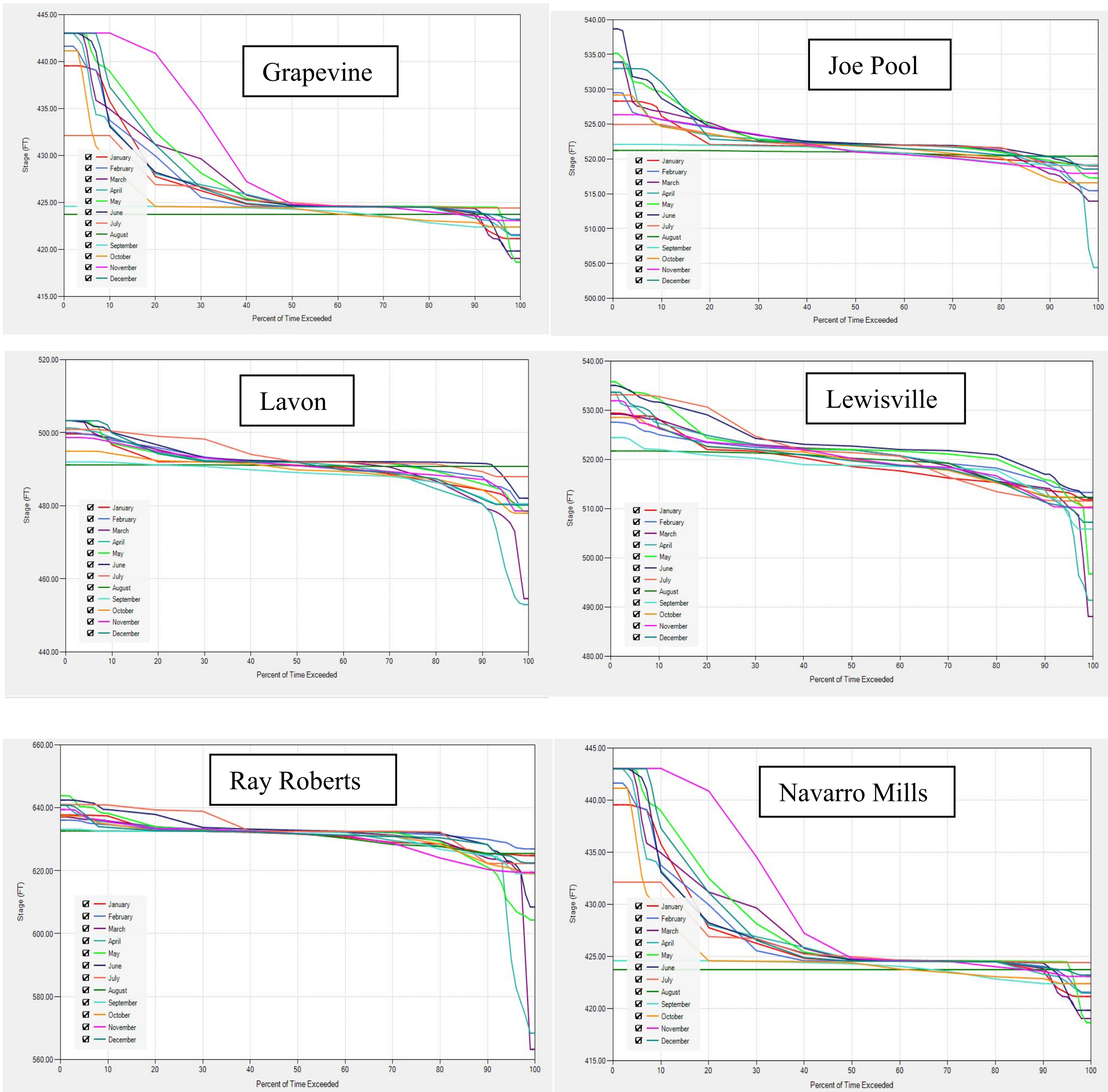


Figure 9.9: Starting Reservor Stage Durations

Table 9.11: Richland-Chambers Starting Pool Elevation for the RMC-RFA Reservoir Simulation Model

Prob.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.999	291.86	292.15	291.83	293.12	289.95	298.03	296.58	295.16	293.93	293.00	292.89	292.37
0.99	292.17	292.47	292.25	297.09	302.32	298.79	297.59	296.13	294.76	293.61	293.39	292.80
0.95	303.35	303.37	303.86	304.19	307.71	307.73	306.65	305.37	304.16	303.16	302.70	302.11
0.90	305.87	306.53	306.97	307.83	308.74	308.90	308.24	307.10	306.27	305.78	305.17	305.60
0.85	307.47	307.97	308.22	308.79	309.17	309.59	309.13	308.22	307.36	307.10	307.36	306.98
0.80	308.58	308.63	309.14	309.46	309.92	311.90	311.18	310.14	309.28	308.72	308.91	308.83
0.75	309.41	309.39	310.03	309.87	312.47	312.58	311.79	310.78	310.07	309.79	309.59	309.31
0.70	310.67	310.64	310.41	310.76	313.05	313.50	312.95	311.99	311.28	310.72	310.28	310.10
0.65	311.09	311.15	312.46	313.47	313.93	314.08	313.36	312.42	311.77	311.48	311.30	311.20
0.60	311.49	312.04	313.40	314.01	314.33	314.33	313.71	312.73	312.03	311.71	311.58	311.42
0.55	312.07	312.73	314.41	314.52	314.52	314.53	313.97	313.02	312.29	311.91	311.70	311.68
0.50	312.66	313.51	314.69	314.69	314.69	314.69	314.15	313.31	312.59	312.13	311.98	311.95
0.45	313.70	314.39	314.85	314.83	314.85	314.83	314.29	313.49	312.83	312.38	312.17	312.50
0.40	314.38	314.81	314.95	314.91	314.97	314.90	314.41	313.63	313.01	312.55	312.44	312.93
0.35	314.92	314.96	314.99	314.97	315.02	314.96	314.51	313.75	313.19	312.75	312.90	314.06
0.30	314.98	314.99	315.03	315.01	315.09	315.02	314.61	313.87	313.30	313.04	313.58	314.33
0.25	315.01	315.03	315.09	315.05	315.16	315.09	314.72	314.00	313.48	313.27	314.46	314.93
0.20	315.04	315.08	315.17	315.12	315.26	315.21	314.84	314.17	313.67	313.47	314.81	315.00
0.15	315.11	315.21	315.27	315.23	315.34	315.31	314.96	314.34	313.91	314.29	315.00	315.10
0.10	315.23	315.32	315.35	315.32	315.38	315.36	315.03	314.57	314.18	314.71	315.08	315.27
0.05	315.35	315.40	315.42	315.39	315.45	315.43	315.23	314.85	314.62	314.99	315.33	315.37
0.01	315.52	315.67	315.82	315.68	315.89	315.65	315.39	315.18	315.18	315.22	315.57	315.77
0.001	315.89	315.92	316.10	316.06	316.32	316.06	315.79	315.45	315.50	315.42	316.14	316.53

9.6.3 Empirical Frequency Curve

For the evaluation of hydrologic hazards of each project, an extreme-value series of annual maximum stage was generated from the n-year systematic (RiverWare + Observed) period of record shown in Table 9.3. Each POR annual maximum series was extracted, the AMS was ranked, and it was plotted on log probability paper using the Weibull plotting position formula shown in Section 9.2. Figure 9.10 is Grapevine Dam's empirical stage frequency relationship when applying the Weibull plotting positions. The systematic frequency peaks for all the projects were plotted against the RMC-RFA pool frequency curves. The plotting position of the highest and lowest points are the most uncertain due to having insufficient record lengths necessary to inform accurate plotting positions at the extremes.

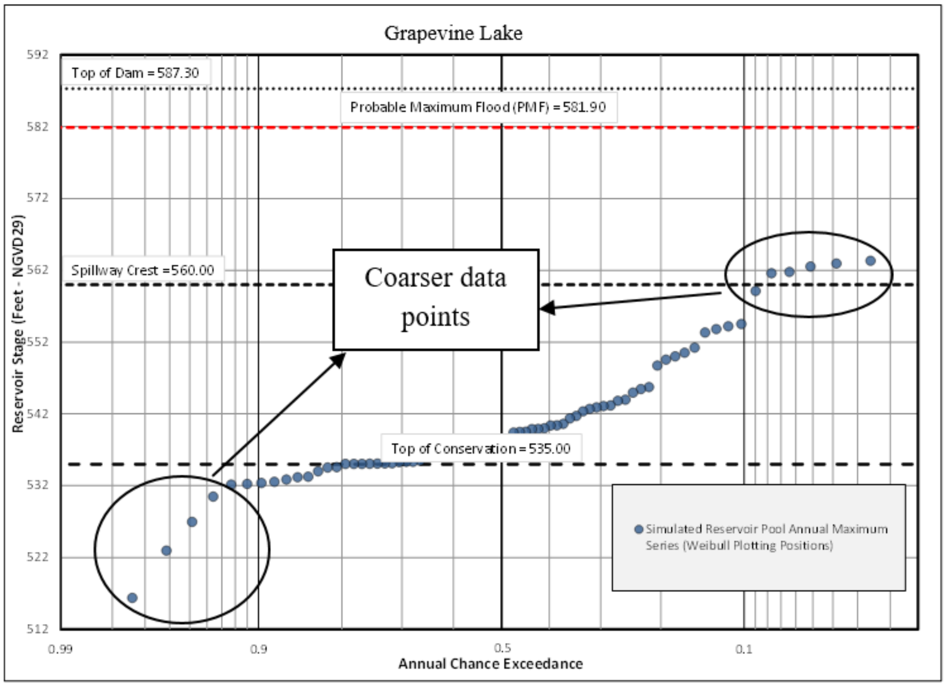


Figure 9.10: Stage Duration Frequency Example for Grapevine Lake

9.6.4 Reservoir Model

The reservoir details such as the Stage-Storage-Discharge function and top of dam, spillway, and inflow design flood elevations were obtained from the Fort Worth District USACE electronic library archived files. The latest Geographic Information System (GIS)-10 meter Digital Elevation Model (DEM) data layers were used and processed through ArcMap-GIS to obtain up to date stage-storage curves for the reservoirs. The Stage-Storage-Discharge information gathered and developed was entered into the Reservoir Model and used to route the inflow hydrographs. The Stage-Storage-Discharge data used for this study can be found in the Appendix E – Reservoir Studies. Pertinenet reservoir stages are listed in Table 9.12.

Table 9.12: Trinity River Basin Lake Pertinent Stages

Project	Bardwell	Benbrook	Grapevine	Joe Pool	Lavon	Lewisville	Navarro Mills	Ray Roberts	Richland Chambers
Pertinent Feature	Elevation (Feet)-NGVD								
Top of Dam	460.0	747.0	588.0	564.5	514.0	560.0	457.0	665.0	330.0
Top of Flood Control Pool	439.0	724.0	560.0	536.0	503.5[1]	532.0	443.0[1]	640.5	315.0
Spillway Crest	439.0	710.0[3]	560.0	541.0[2]	475.5	532.0	414.0	645.5[2]	315.0
Top of Conservation Pool	421.0	694.0	535.0	522.0	492.0	522.0	424.5	632.5	-

[1] at notch in emergency spillway. [2] at crest of perched emergency spillway. [3] at top of closed tainter gates.

9.7 RESULTS

The RMC-RFA program was used to simulate rainfall-runoff floods using the inflow-frequency curve and the adopted flood seasonality. The specified hourly inflow hydrographs were weighted equally to account for each unique shape (*i.e.* volume and peak) and to have the same probability. A routing time window of 5 days was specified to calculate the full size of floods routed through the reservoir on an hourly basis. The RMC-RFA model was simulated using the expected stage frequency curve only model option. This runs 10,000 realizations with 1,000,000 events per realization. This means RMC-RFA simulates a total of 10 billion events (10,000 x 1,000,000) to produce its best estimate of the expected curve. Each federally owned project has a flowage easement elevation.

The results were first obtained utilizing the RMC-RFA program. Once ran, a second look at the results was deemed necessary to ensure accurate results are maintained. Accurate results lie in fitting the best estimate pool frequency curves through the observed elevation data points for the more frequent events, generally within the 50% to 2% AEP range, which is highly representative by the observed AMS data. For rare events such as the 1%ACE (100-year) and 0.2%ACE (500-year), a second adjustment was made using best engineering judgment and knowledge of operations during high peak events. The final adopted curves were thus the combined results of modeling and best engineering judgment efforts. A sample pool frequency curve is included below (Figure 9.11). Recommended pool-frequency and discharge-frequency values are summarized in Table 9.13 and Table 9.14 . Effective FEMA FIS information was also compared where available (Table 9.15 and Table 9.16). All pool frequency curves as well as additional details regarding the RMC-RFA results can be found in Appendix E – Reservoir Studies.

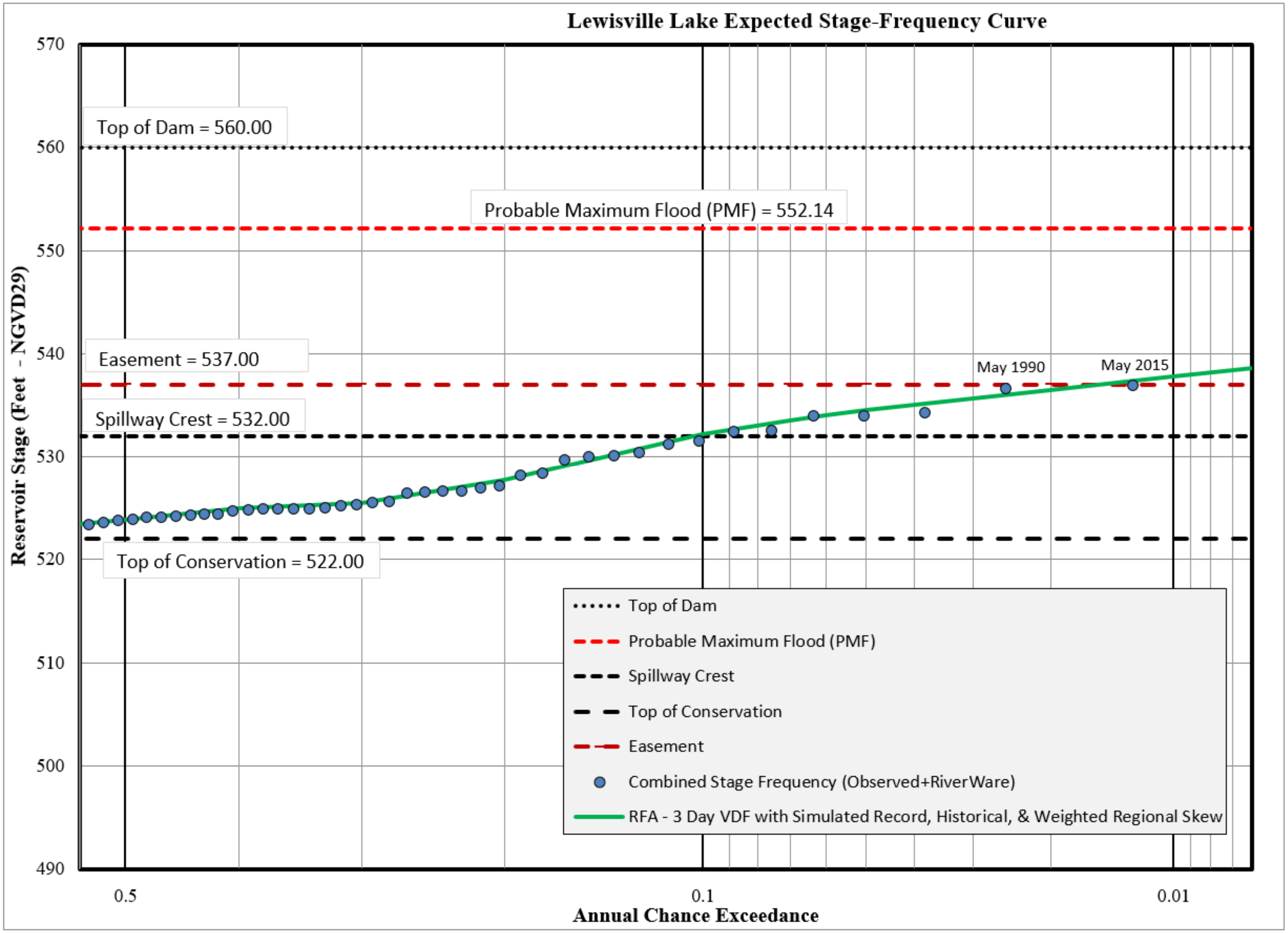


Figure 9.11: Lewisville Dam Current Conditions (2016) Stage-Frequency Curve

Table 9.13: RMC-RFA Stage-Frequency Results (Feet-NGVD)

Annual Chance of Exceedance	Return Period	Bardwell	Benbrook	Grapevine	Joe Pool	Lavon	Lewisville	Navarro Mills	Ray Roberts	Richland-Chmbers
%	years									
50%	2	425.69	697.20	538	524.50	493.90	523.88	430.90	633.25	315.90
20%	5	430.94	704.00	546	527.00	499.50	527.75	436.10	635.70	316.30
10%	10	434.50	711.00	556	531.00	502.80	532.15	439.84	639.50	316.60
4%	25	438.10	713.73	561.54	535.30	503.70	535.02	443.20	641.10	317.10
2%	50	440.00	715.68	562.83	537.50	504.00	536.50	444.00	644.00	317.40
1%	100	441.50	717.57	564	539.00	504.30	537.75	444.50	645.50	317.60
0.40%	250	443.21	720.27	565.61	540.80	504.70	539.26	445.23	647.20	318.00
0.20%	500	444.24	722.29	566.91	542.17	505.00	540.50	445.74	648.50	318.30

Table 9.14: Total Outflow (cfs) from Dam Based on RMC-RFA Stage-Frequency Results

Annual Chance of Exceedance	Return Period	Bardwell	Benbrook	Grapevine	Joe Pool	Lavon	Lewisville	Navarro Mills	Ray Roberts	Richland-Chmbers
%	years									
50%	2	1,200	3,000	2,000	1,200	4,000	4,000	1,000	2,000	13,100
20%	5	2,000	6,000	2,000	2,400	8,000	7,000	2,000	4,000	25,900
10%	10	2,000	6,000	2,000	4,000	8,000	7,000	2,000	7,000	37,400
4%	25	2,000	6,000	3,100	4,000	10,665	9,400	3,000	7,000	62,600
2%	50	2,000	6,000	7,700	4,000	22,000	17,900	7,000	7,000	91,800
1%	100	4,335	6,700	13,100	4,000	35,200	26,500	9,900	7,000	111,300
0.40%	250	6,060	10,900	22,200	4,000	53,600	38,900	15,300	7,000	150,300
0.20%	500	9,470	14,600	30,800	4,000	66,000	50,000	21,000	7,000	193,000

Table 9.15: RMC-RFA Stage-Frequency Results (Feet NGVD) - Comparison with FEMA FIS Results

Annual Chance of Exceedance	Return Period	Benbrook	Benbrook	Grapevine	Grapevine	Joe Pool	Joe Pool	Lewisville	Lewisville	Ray Roberts	Ray Roberts
%	years	Res. Study	FEMA FIS	Res. Study	FEMA FIS	Res. Study	FEMA FIS	Res. Study	FEMA FIS	Res. Study	FEMA FIS
50%	2	697.20		538		524.50		523.88		633.25	
20%	5	704.00		546		527.00		527.75		635.70	
10%	10	711.00	704.8	556	554.0	531.00	527.5	532.15	529.5	639.50	639.5
4%	25	713.73		561.54		535.30		535.02		641.10	
2%	50	715.68	712.2	562.83	562.3	537.50	536.0	536.50	535.0	644.00	644.0
1%	100	717.57	715.0	564	564.0	539.00	537.5	537.75	537.0	645.50	645.5
0.40%	250	720.27		565.61		540.80		539.26		647.20	
0.20%	500	722.29	727.0	566.91	568.4	542.17	543.5	540.50	541.0	648.50	649.0

Table 9.16: Total Outflow (cfs) from Dam Based on RMC-RFA Stage-Frequency Results - Comparison with FEMA FIS Results

Annual Chance of Exceedance	Return Period	Benbrook	Benbrook	Grapevine	Grapevine	Joe Pool	Joe Pool*	Lewisville	Lewisville	Ray Roberts	Ray Roberts
%	years	Res. Study	FEMA FIS	Res. Study	FEMA FIS	Res. Study	FEMA FIS	Res. Study	FEMA FIS	Res. Study	FEMA FIS
50%	2	3,000		2,000		1,200		4,000		2,000	
20%	5	6,000		2,000		2,400		7,000		4,000	
10%	10	6,000	6,000	2,000	4,000	4,000	34,100	7,000	6,300	7,000	6,300
4%	25	6,000		3,100		4,000		9,400		7,000	
2%	50	6,000	8,400	7,700	7,000	4,000	59,400	17,900	9,000	7,000	9,000
1%	100	6,700	13,000	13,100	9,400	4,000	74,700	26,500	21,000	7,000	10,238
0.40%	250	10,900		22,200		4,000		38,900		7,000	
0.20%	500	14,600	46,000	30,800	36,200	4,000	103,800	50,000	55,000	7,000	12,800

*Mountain Creek discharges (At Camp Wisdom Rd) below Joe Pool Dam do not reflect flood reduction benefits of dam. Currently effective flows exceed PMF discharges from Joe Pool Dam.

10 Comparison of Frequency Flow Estimates

After completing the hydrologic analyses by all the various methods described in this report, their results were compared to one another in terms of frequency peak discharge estimates at the USGS stream gage locations. These comparisons of frequency flow estimates are given in Table 10.1 to Table 10.73. Blank cells indicate data was not available at the specific location. Figure 10.1 through Figure 10.92 plot the estimated frequency curves at each gage along with their confidence limits and the previous published discharges from the effective FEMA Flood Insurance Studies (FIS). Additional discussion and a summary of the recommended results is included in the next section.

Table 10.1: Comparison of Frequency Flows at West Fork Trinity River near Jacksboro Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				122,700		91,500	79,500	
0.004	200				76,400		65,100	56,200	
0.01	100				52,100		48,200	40,700	
0.02	50				34,600		30,600	26,300	
0.04	25				22,100		20,300	17,800	
0.1	10				11,300		11,400	10,600	
0.2	5				6,200		6,100	5,900	
0.5	2				2,000		2,100	1,900	

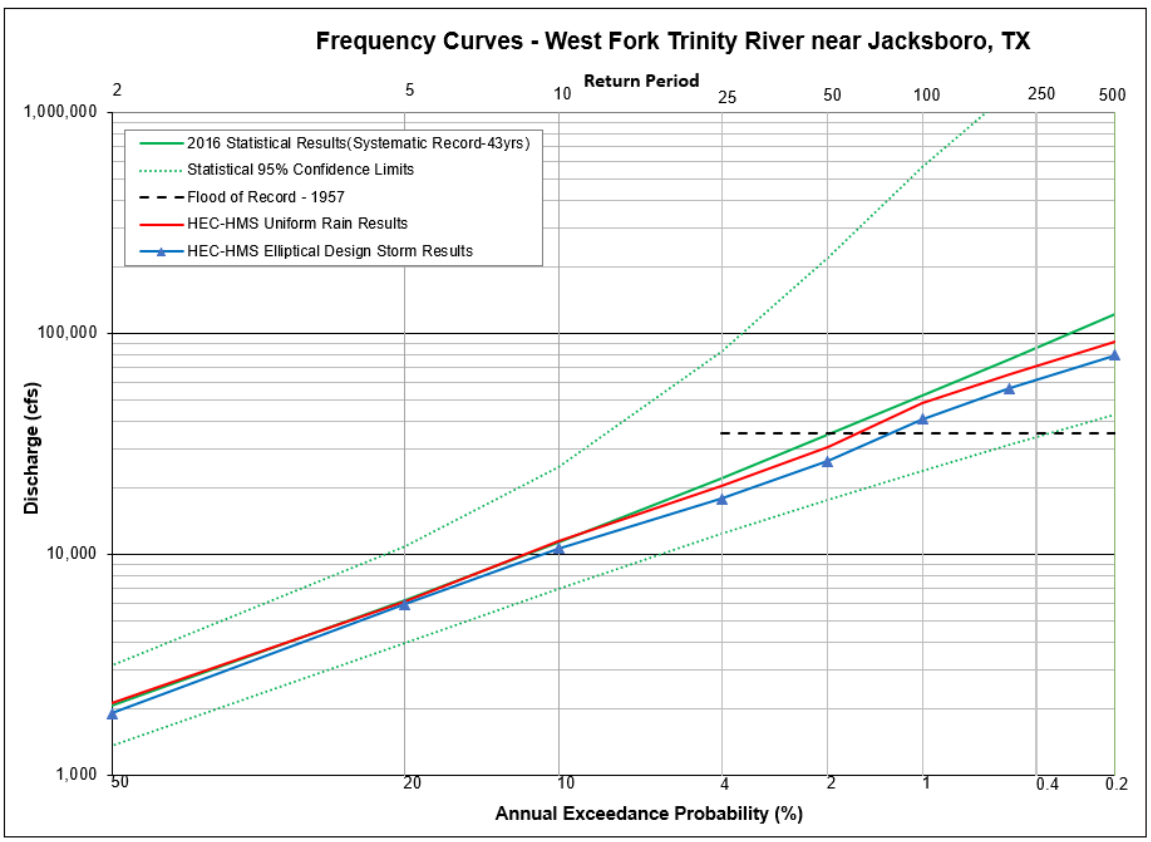


Figure 10.1: Flow Frequency Curve Comparison for West Fork Trinity River near Jacksboro Gage

Figure 10.2 below provides a comparison between the 100-year calibrated rainfall-runoff model (HEC-HMS) results, observed annual peak flows, 100-year USGS regression equation results, and 100-year statistical hydrology results for the West Fork Trinity River near Jacksboro USGS gage. The statistical hydrology results show how the 100-year statistical hydrology value has changed as each additional annual peak flow is added to the record. Generally, at least 300-400 years of record are needed before the 1% annual chance (100-yr) flow frequency estimates will stop significantly changing over time with additional year of record, unless additional information such as rainfall-runoff modeling estimates are utilized in the statistical analysis.

For this location, the HEC-HMS results have been both higher and lower than the statistical hydrology estimate as the statistical hydrology result has changed over time. The HEC-HMS results are well within the statistical hydrology 95% confidence limits and are similar to the statistical hydrology estimate using the full record length. The HEC-HMS results are similar to the USGS regression equation value, which considers the drainage area below USACE reservoirs and other major reservoirs.

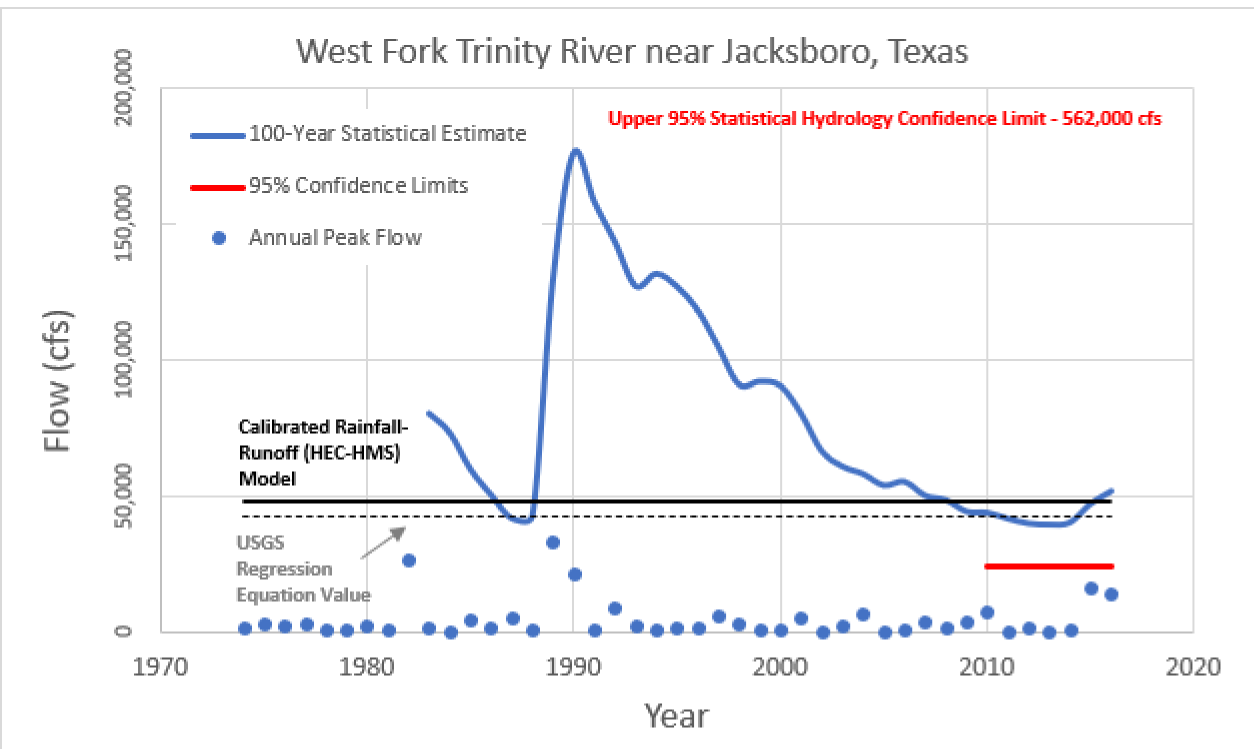


Figure 10.2 100-YR Flow Frequency Comparison for West Fork Trinity River near Jacksboro Gage

Table 10.2: Comparison of Frequency Flows for Lost Creek Reservoir Outflow

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500						15,900		
0.004	200						12,700		
0.01	100	16,800		16,800			10,200		
0.02	50						7,200		
0.04	25						4,500		
0.1	10						1,600		
0.2	5						900		
0.5	2						240		

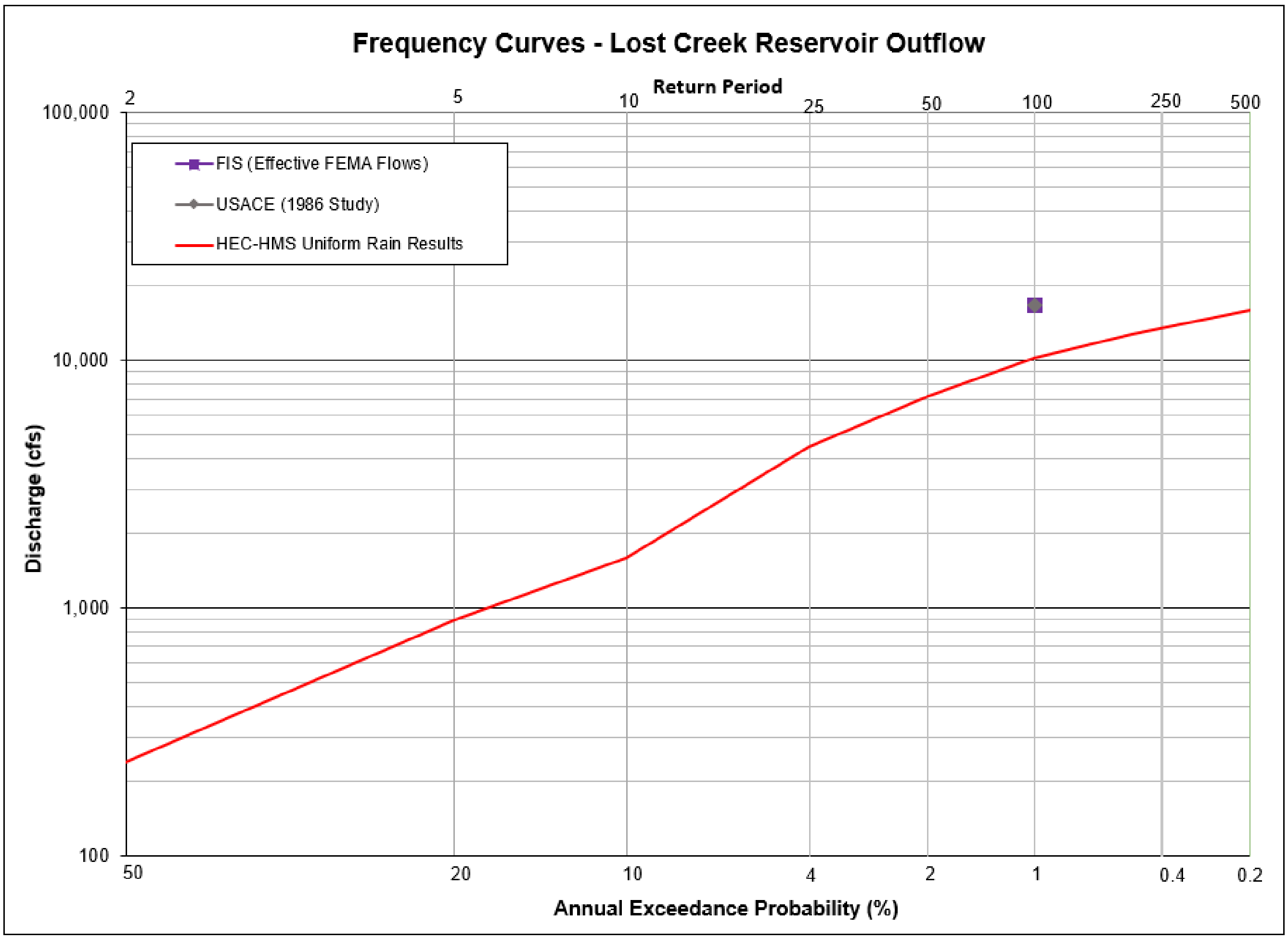


Figure 10.3: Flow Frequency Curve Comparison for Lost Creek Reservoir Outflow

Table 10.3: Comparison of Frequency Flows at Big Sandy Creek near Bridgeport Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				115,100		65,000	64,600	
0.004	200				78,400		48,100	47,000	
0.01	100				57,100		37,800	36,600	
0.02	50				40,400		26,600	26,200	
0.04	25				27,400		19,100	18,800	
0.1	10				15,100		11,600	12,300	
0.2	5				8,600		7,100	7,900	
0.5	2				2,900		2,700	3,600	

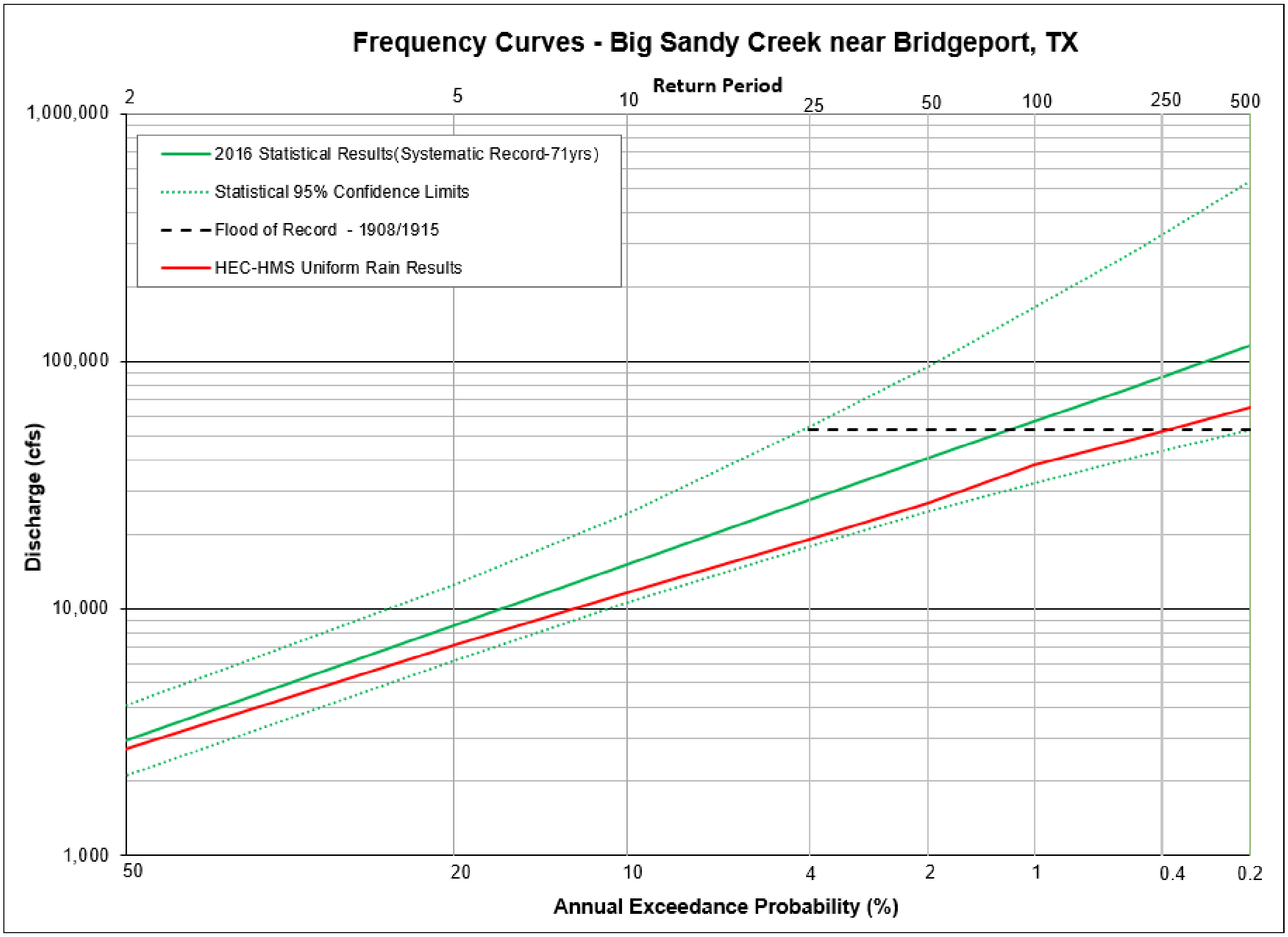


Figure 10.4: Flow Frequency Curve Comparison for Big Sandy Creek near Bridgeport Gage

Table 10.4: Comparison of Frequency Flows at West Fork Trinity River near Boyd Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				144,300		101,100	96,400	
0.004	200				93,100		76,400	71,500	
0.01	100				65,300		58,700	54,700	
0.02	50				44,600		40,600	38,200	
0.04	25				29,500		28,500	26,700	
0.1	10				15,900		17,000	16,800	
0.2	5				9,000		10,000	9,300	
0.5	2				3,300		3,600	3,000	

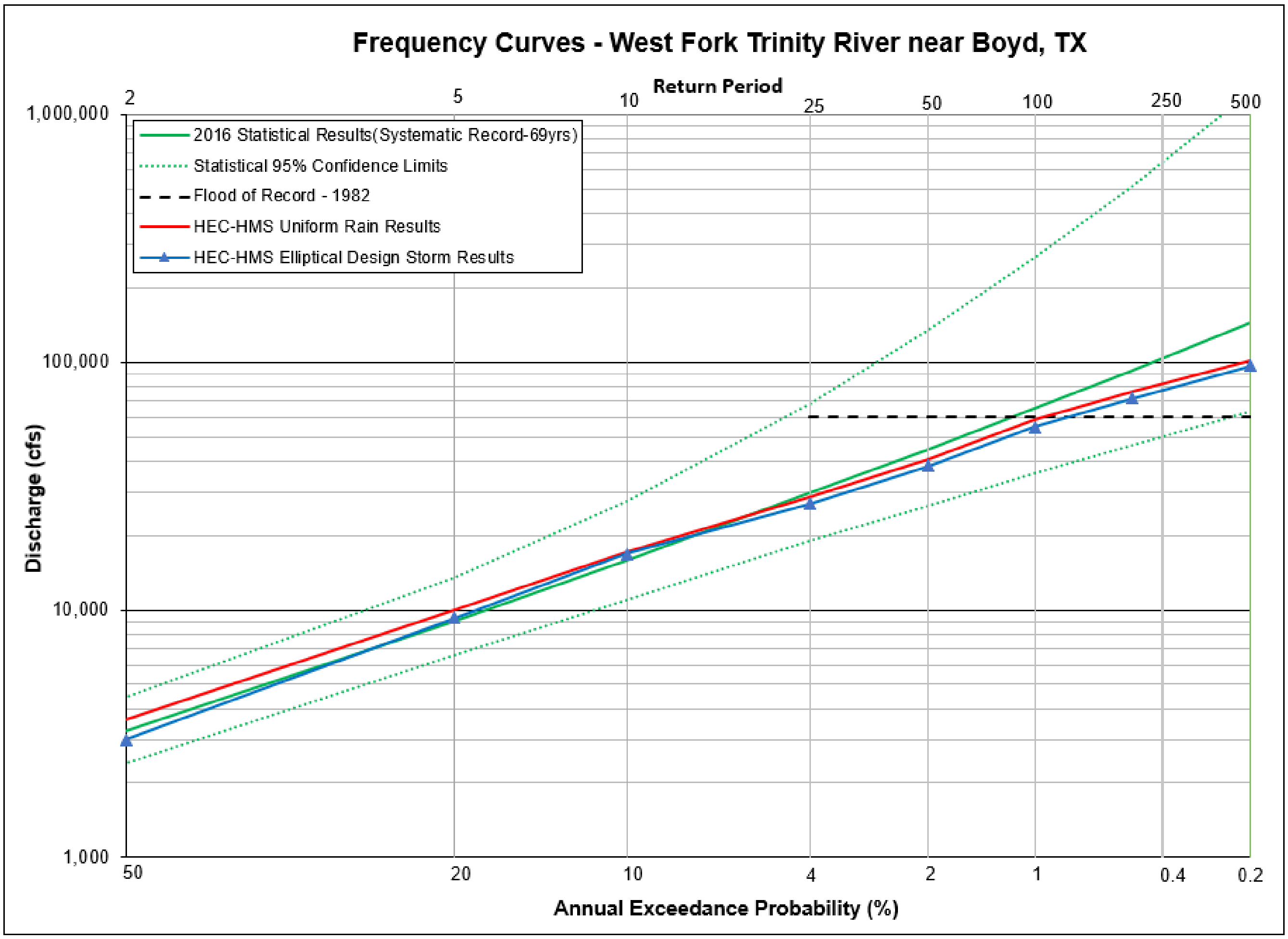


Figure 10.5: Flow Frequency Curve Comparison for West Fork Trinity River near Boyd Gage

Figure 10.6 below provides a comparison between the 100-year calibrated rainfall-runoff model (HEC-HMS) results, observed annual peak flows, 100-year USGS regression equation results, and 100-year statistical hydrology results at the West Fork Trinity River near Boyd USGS gage. The statistical hydrology results show how the 100-year statistical hydrology value has changed as each additional annual peak flow is added to the record. Generally, at least 300-400 years of record are needed before the 1% annual chance (100-yr) flow frequency estimates will stop significantly changing over time with additional year of record, unless additional information such as rainfall-runoff modeling estimates are utilized in the statistical analysis.

For this location, the HEC-HMS results have been both higher and lower than the statistical hydrology estimate as the statistical hydrology result has changed over time. The HEC-HMS results are well within the statistical hydrology 95% confidence limits and is slightly lower than the statistical hydrology estimate using the full record length. The HEC-HMS results are also slightly lower than the USGS regression equation value, which considers the drainage area below USACE reservoirs and other major reservoirs..

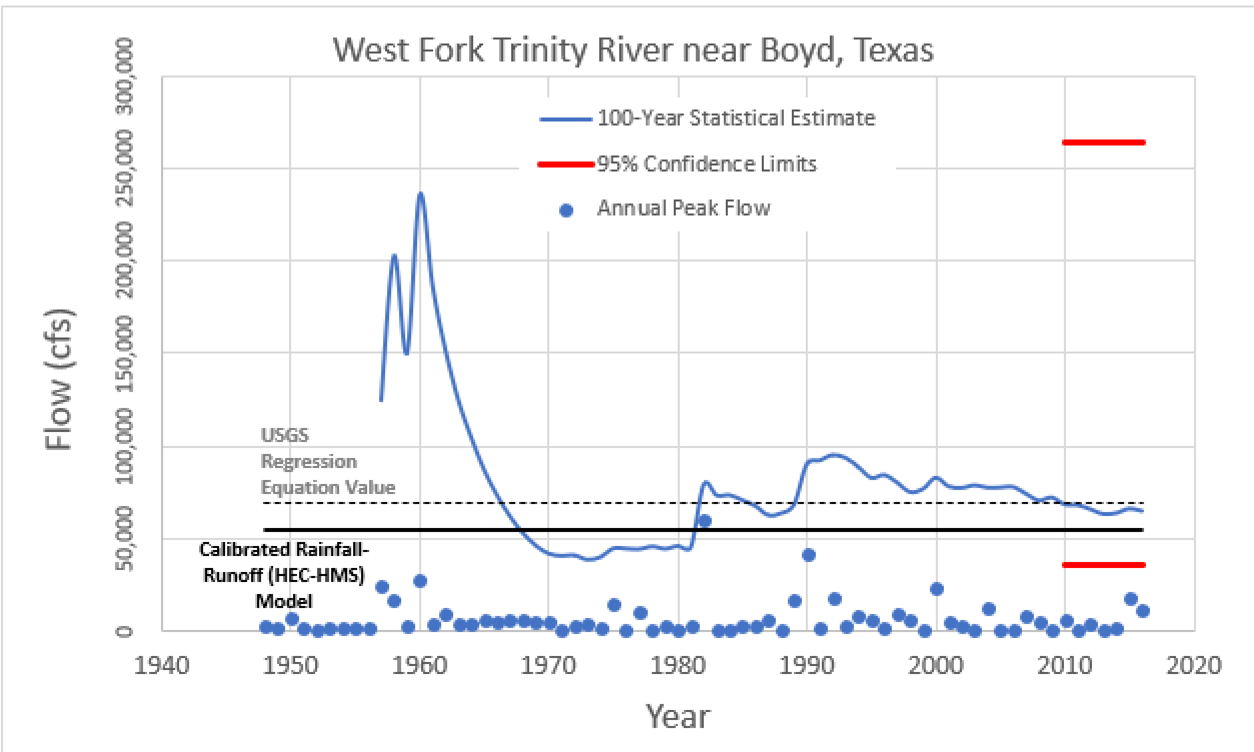


Figure 10.6 100-YR Flow Frequency Comparison for West Fork Trinity River near Boyd Gage

Table 10.5: Comparison of Frequency Flows at Walnut Creek at Reno Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				54,000		54,900		
0.004	200				44,200		47,200		
0.01	100				37,000		41,400		
0.02	50				30,000		34,900		
0.04	25				23,300		29,100		
0.1	10				15,200		19,800		
0.2	5				9,700		13,000		
0.5	2				3,600		5,000		

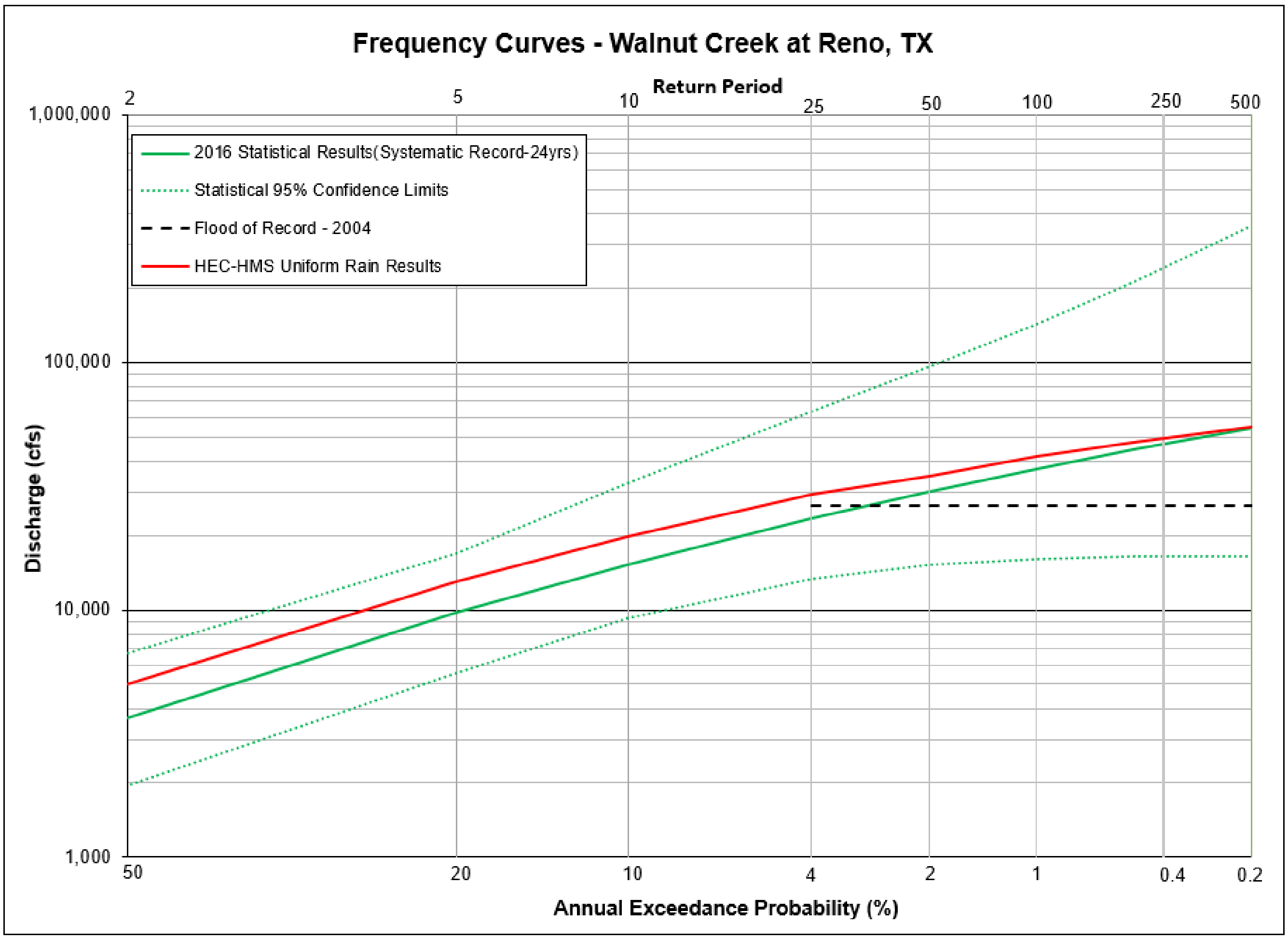


Figure 10.7: Flow Frequency Curve Comparison for Walnut Creek at Reno Gage

Table 10.6: Comparison of Frequency Flows for Eagle Mountain Reservoir Outflow

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	56,300		48,300			56,000	42,500	
0.004	200						38,900	33,000	
0.01	100	31,900		35,600			30,400	27,100	
0.02	50	21,900		28,700			23,300	21,500	
0.04	25			23,300			19,000	17,200	
0.1	10	9,200		14,500			14,100	13,800	
0.2	5			13,500			7,300	7,300	
0.5	2			7,700			3,700	3,800	

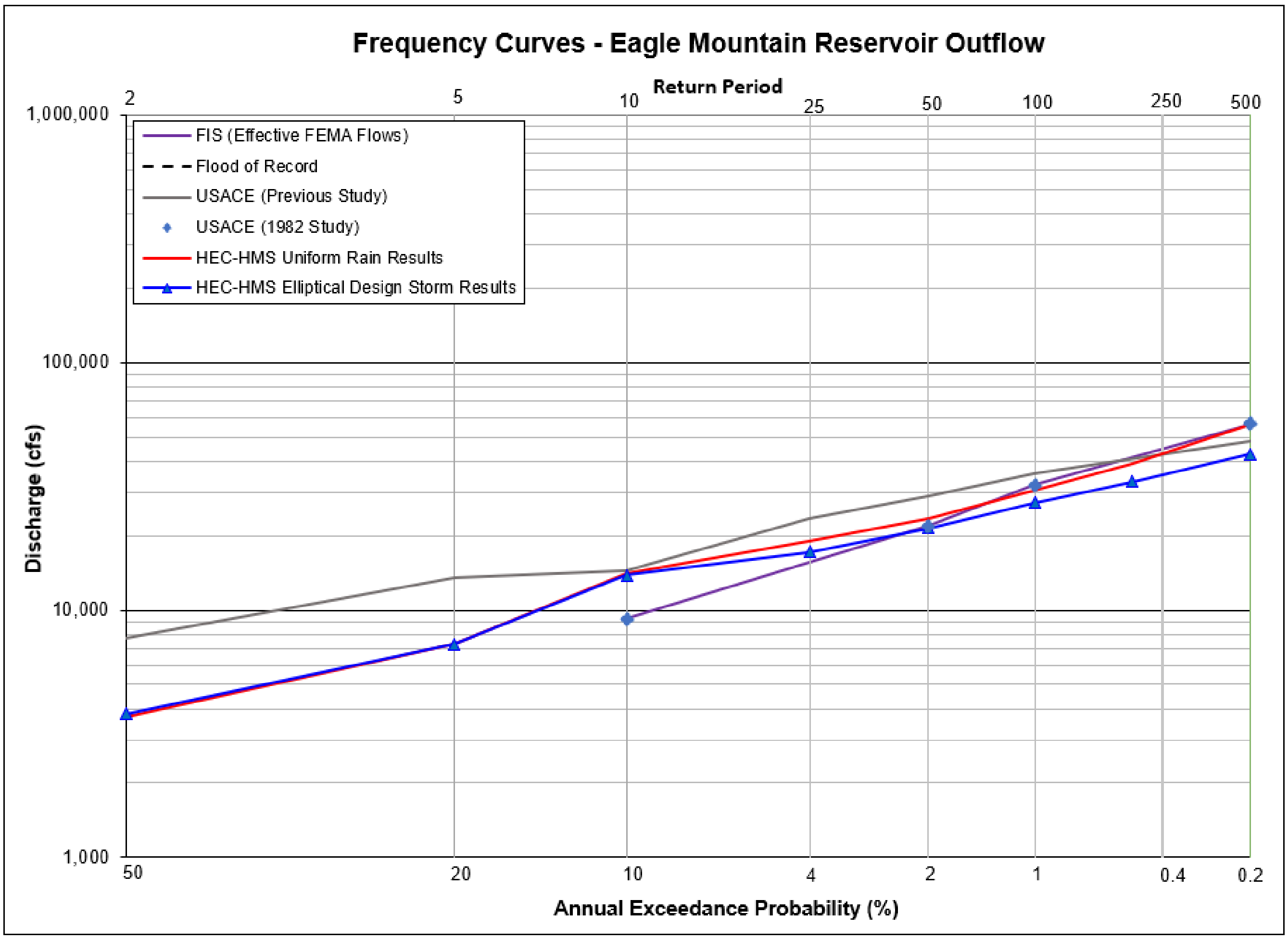


Figure 10.8: Flow Frequency Curve Comparison for Eagle Mountain Reservoir Outflow

Table 10.7: Comparison of Frequency Flows for Lake Worth Outflow

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	54,600		54,600			56,400	42,800	
0.004	200						39,200	33,400	
0.01	100	35,200		35,200			30,700	27,400	
0.02	50	28,400		28,400			23,400	21,600	
0.04	25			28,400			19,300	17,400	
0.1	10	14,300		14,300			14,300	13,900	
0.2	5			13,400			7,400	7,300	
0.5	2			7,500			3,500	3,000	

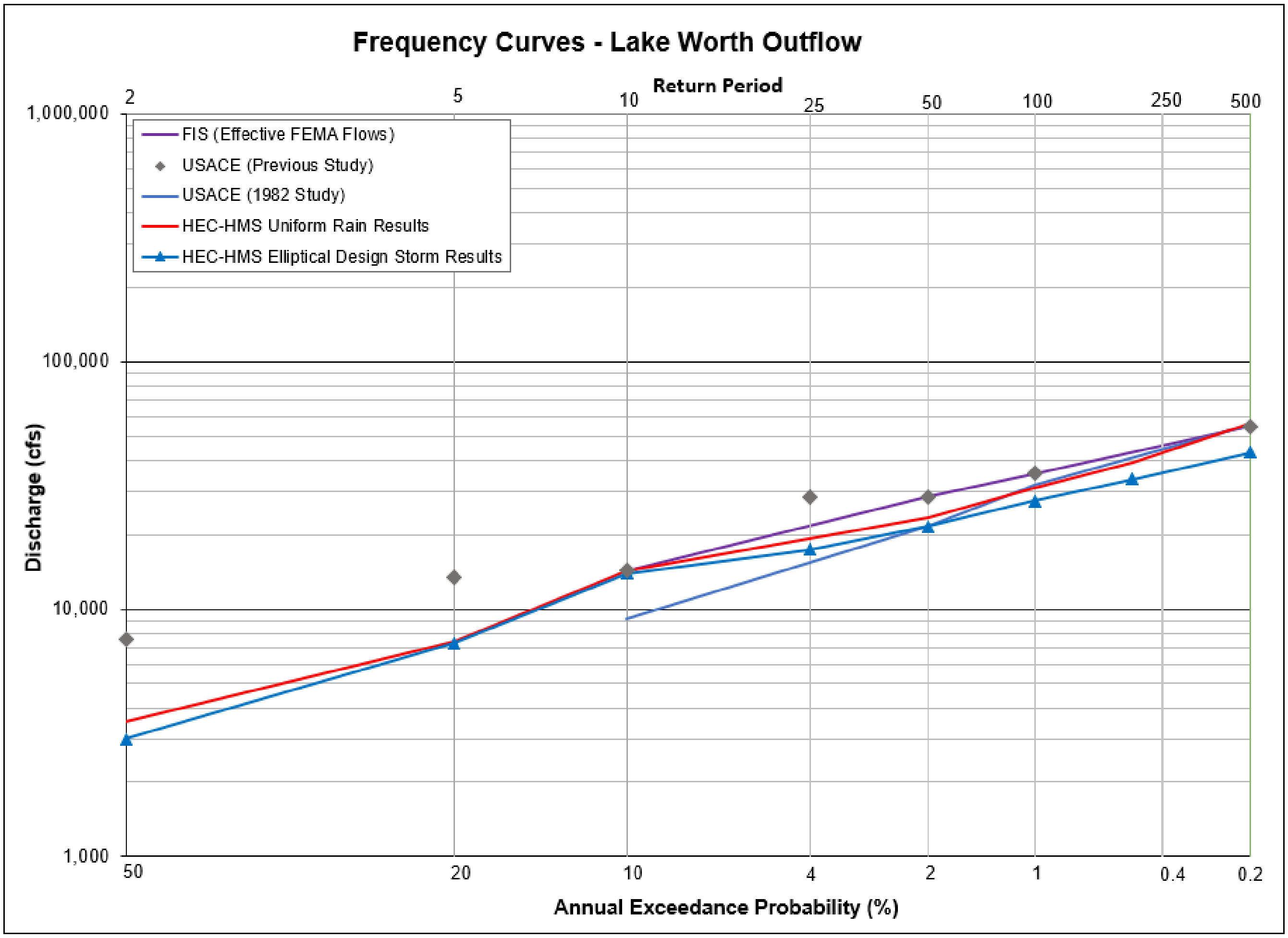


Figure 10.9: Flow Frequency Curve Comparison for Lake Worth Outflow

Table 10.8: Comparison of Frequency Flows for Lake Weathorford Outflow

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	31,800		31,800			38,800		
0.004	200						26,300		
0.01	100	16,100		8,800			18,500		
0.02	50	5,700		5,700			8,600		
0.04	25						5,100		
0.1	10	3,000		3,000			3,000		
0.2	5						2,100		
0.5	2						800		

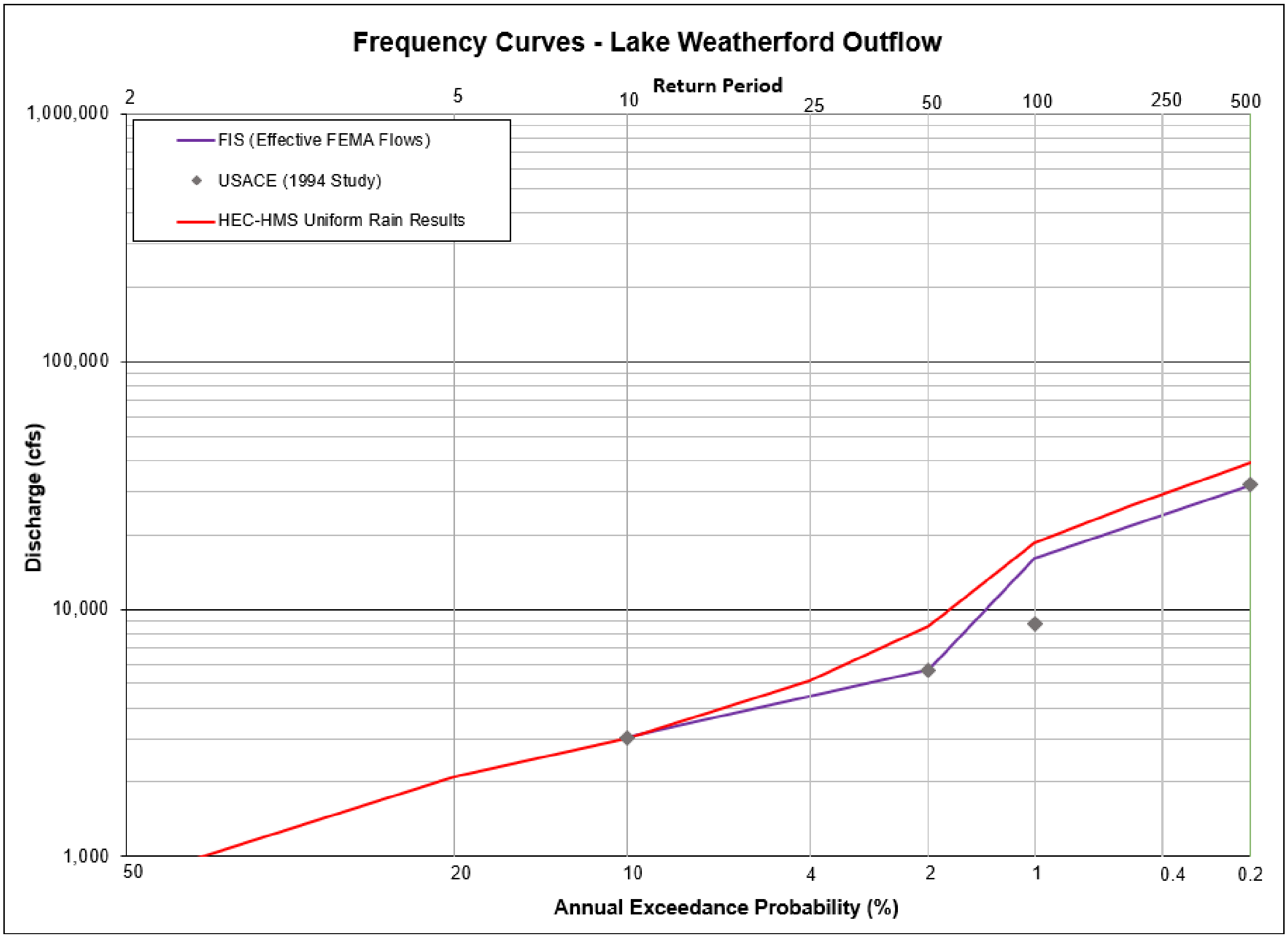


Figure 10.10: Flow Frequency Curve Comparison for Lake Weatherford Outflow

Table 10.9: Comparison of Frequency Flows at Clear Fork Trinity River near Weathorfod Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	31,700		31,700	14,100				
0.004	200				10,100				
0.01	100	8,800		8,800	7,700				
0.02	50	6,700		6,700	5,800				
0.04	25				4,100				
0.1	10	4,900		4,900	2,500				
0.2	5				1,500				
0.5	2				600				

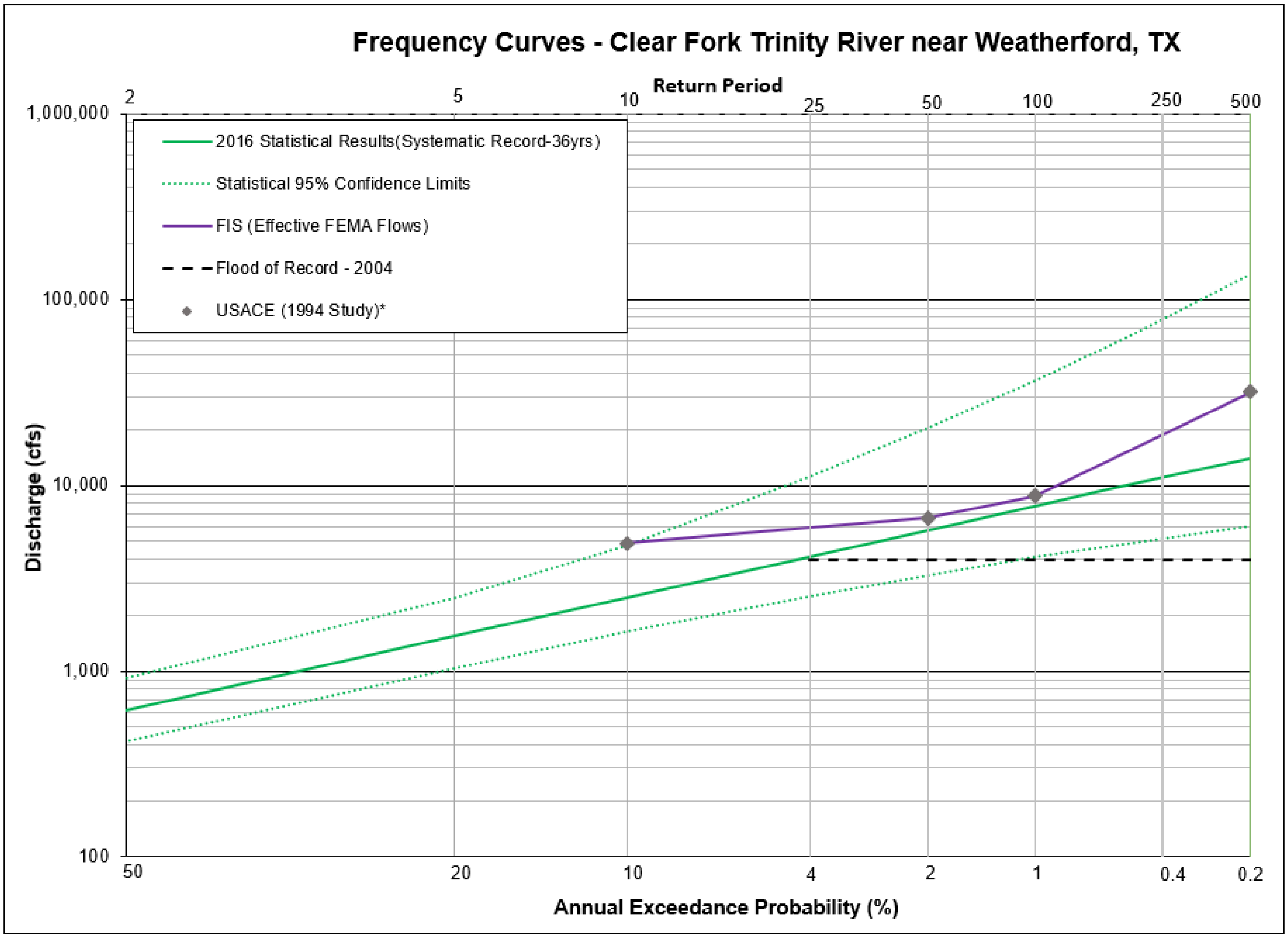


Figure 10.11: Flow Frequency Curve Comparison for Clear Fork Trinity River near Weatherford Gage

Table 10.10: Comparison of Frequency Flows at Clear Fork Trinity River at Kelly Rd Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	75,800		75,800			72,100		
0.004	200						49,700		
0.01	100	46,800		46,800			34,800		
0.02	50	32,000		32,000			23,100		
0.04	25						17,600		
0.1	10	16,000		16,000			11,000		
0.2	5						6,200		
0.5	2						2,100		

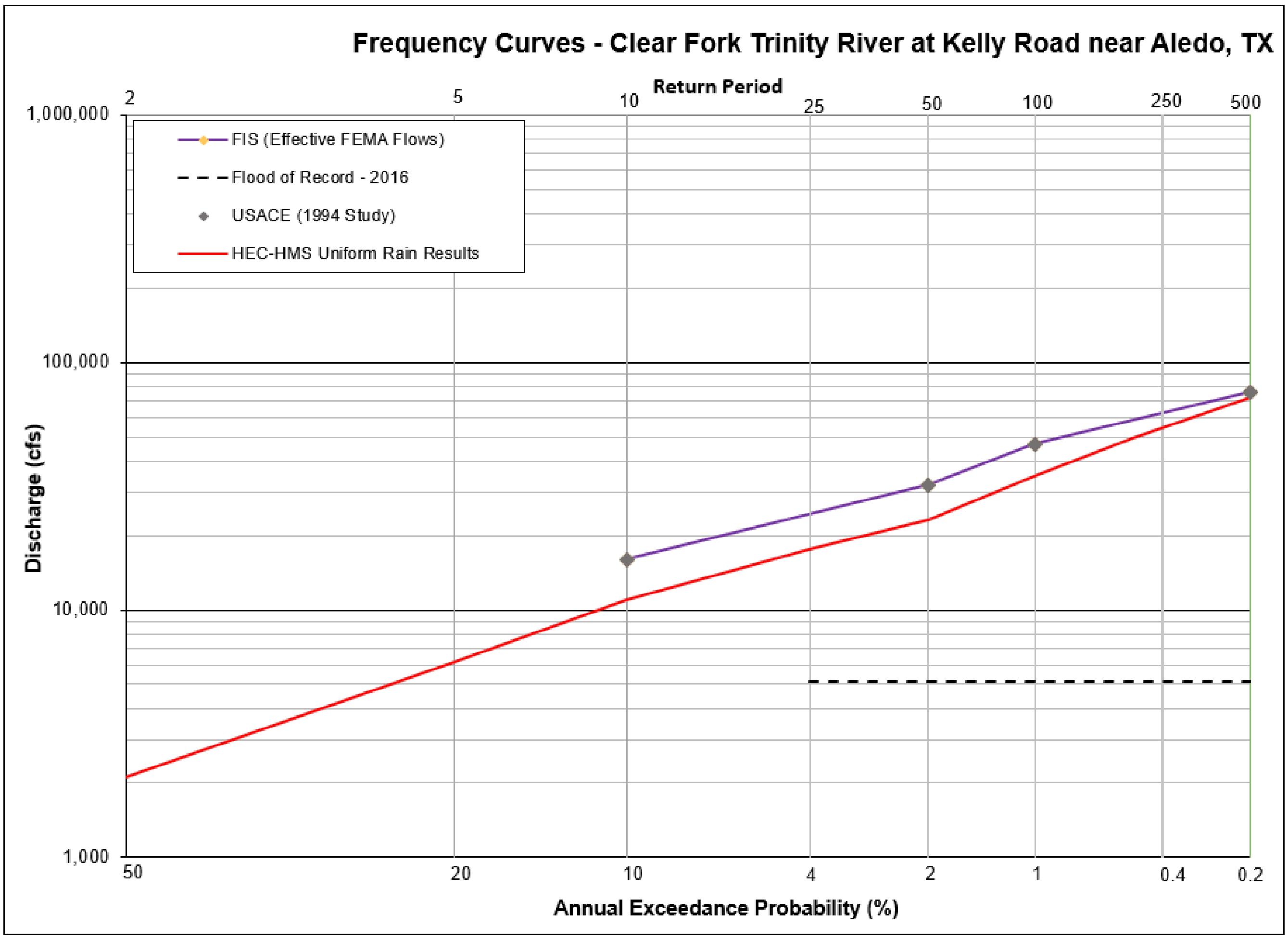


Figure 10.12: Flow Frequency Curve Comparison for Clear Fork Trinity River at Kelly Rd near Aledo Gage

The Benbrook Outflow (Clear Fork Trinity River near Benbrook) location has several results that can be compared. First, while the Reservoir Study, Statistical Hydrology, and HEC-HMS Uniform Rainfall Methods are all in agreement for their estimates of the 1% annual chance event, there are some differences in their estimates other frequency events based on the assumptions and techniques used by the different methods. The 1% annual chance values from these methods are also very similar to the highest observed value (6,700 cfs, May 1990) since the construction of Benbrook Dam. The currently effective FEMA FIS results are higher than those developed from the various hydrologic methods used in this study. One significant difference between the FIS results and the current results is the additional decades of observed information that were incorporated into Riverware Analysis, Statistical Hydrology, and Reservoir study. The Reservoir Study is generally considered the most comprehensive method for the analysis of outflows from the dams. This is a stochastic method that samples input variables and accounts for different starting pool elevations as well as diiferent inflow hydrograph shapes and volumes. This paints a more comprehensive picture of stage and outflow frequency estimates for reservoirs.

Table 10.11: Comparison of Frequency Flows for Benbook Lake Outflow

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	46,000	46,000	46,000	8,700	16,100	22,600		14,600
0.004	200				7,800	12,500	12,300		9,900
0.01	100	13,000	13,000	13,000	7,100	10,100	7,600		6,700
0.02	50	8,400	7,500	8,400	6,300	8,000	4,200		6,000
0.04	25		6,000	6,800	5,300	5,600	1,800		6,000
0.1	10	6,000	6,000	6,000	4,000	4,000	0		6,000
0.2	5			3,700	2,800	2,700	0		6,000
0.5	2			2,300	1,300	1,200	0		3,000

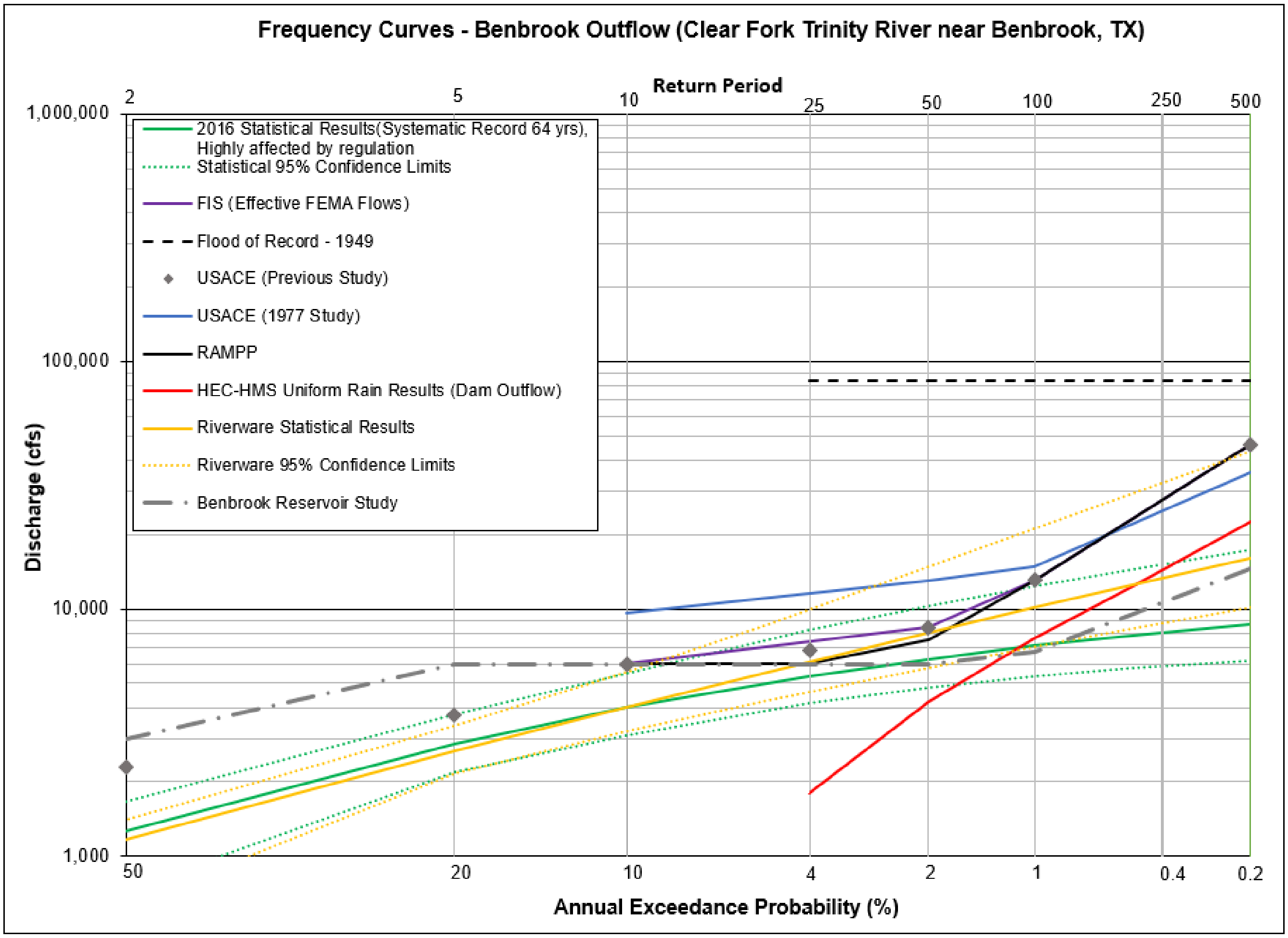


Figure 10.13: Flow Frequency Curve Comparison for Benbrook Lake Outflow

The Mary's Creek at Benbrook location has several results that can be compared. First the 1% annual chance results between the HEC-HMS Uniform Rainfall and Statistical Hydrology methods are very similar. However, this gage has a very short record length (18 years) relative to estimating values for the 100-yr recurrence interval or 1% annual chance event. The HEC-HMS Uniform Rainfall results are higher than the currently effective FIS results. The main difference between the FIS results and the current results is that extensive calibration and model investigation was performed for the current study, while the original FIS did not have a streamflow gage on Mary's Creek available for calibration and so model parameters were not modified from the initial estimates .

Model calibration was performed for observed storm events that have occurred over the past 18 years. Because of the limited record length and storms available for calibration, generally considered to have recurrence intervals around the 5-10-yr level, a unit hydrograph peaking study was performed using the rain-on-mesh 2-dimensional modeling capabilities of HEC-RAS. The purpose of this study was to investigate how well the calibrated model would simulate the watershed response to a larger and more intense event on the scale of a 1% annual chance event. The results of the unit hydrograph peaking study indicated that additional peaking beyond the calibrated parameters would likely occur for a 1% annual chance event. Figure 10.14 shows how the lag time is reduced for less frequent storm events with greater runoff volumes. For example the 2-yr lag time is about 2.8 hours, while the 100-yr lag time is about 1.5 hours. Where precipitation volumes are equal, shorter lag times result in higher peak discharges than longer lag times for a watershed. These findings are consistent with findings from other published unit hydrograph peaking studies. Regionalized equations were developed from the study and utilized in the HEC-HMS Uniform Rainfall modeling for this study. Additional details regarding the unit hydrograph peaking study can be found in Appendix F- USACE 2-Dimensional HEC-RAS Analysis of Mary's Creek.

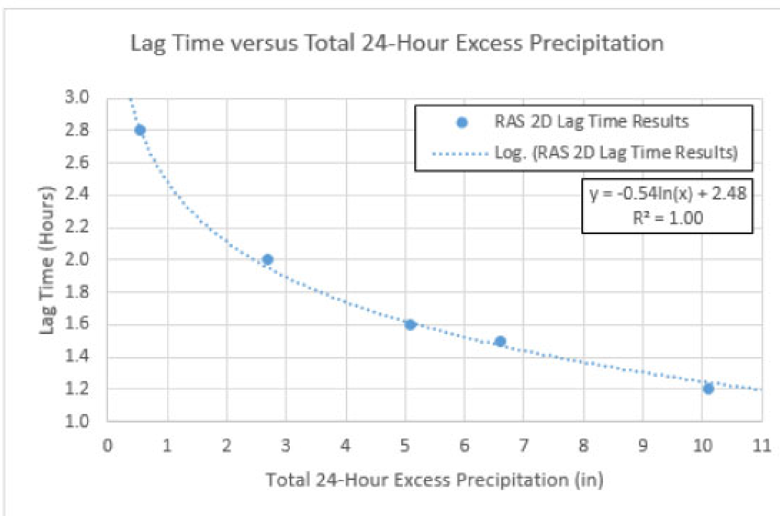


Figure 10.14 Reduction in Lag Time with Increase in Storm Volume

The HEC-HMS Uniform Rainfall modeling results are the recommended results for this location as they are based on the best available precipitation data, which has been very consistent over time within the DFW area as well as the best available representation of the physical watershed response to a large event such as the 1% annual chance event.

Additionally, a very simple storm shift study was performed using the HEC-RAS model from the unit hydrograph peaking study to see the impacts of a large rainfall event that fell in the region but was centered just above Benbrook Lake. The June 2000 event had 24 hour point totals of 10+ inches and was centered upstream of Benbrook Lake. This was one of the Mary's Creek HEC-HMS calibration events. The storm was shifted (transposed) about 15 miles to the North where it was moved over Mary's Creek. Using the same loss rates from the HEC-HMS calibration, the model indicated a potential peak flow of between 60-70k cfs at the Mary's Creek gage, which would have exceeded the currently effective flows, even with very high losses. Significant impact to property and lives would have been likely if this storm had been centered 15 miles north of where it actually occurred. The shifted storm results are very similar to the HEC-HMS Uniform Rainfall 1% annual chance results.

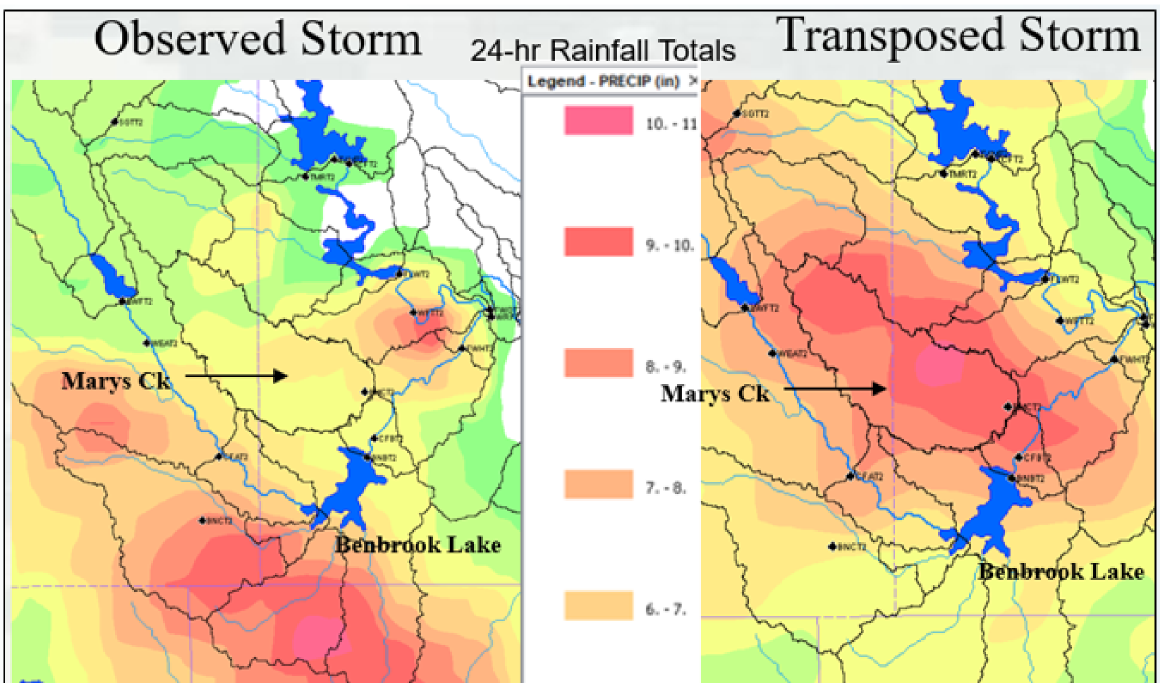


Figure 10.15: June 2000 Storm Shift Over Mary's Creek

Table 10.12: Comparison of Frequency Flows at Marys Creek at Benbrook Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	56,300		61,000	122,100		92,500		
0.004	200				86,800		77,000		
0.01	100	43,400		44,900	65,300		63,100		
0.02	50	36,900		38,900	47,600		52,700		
0.04	25				33,400		43,500		
0.1	10	25,700		25,200	19,200		25,100		
0.2	5				11,300		12,400		
0.5	2				4,000		2,500		

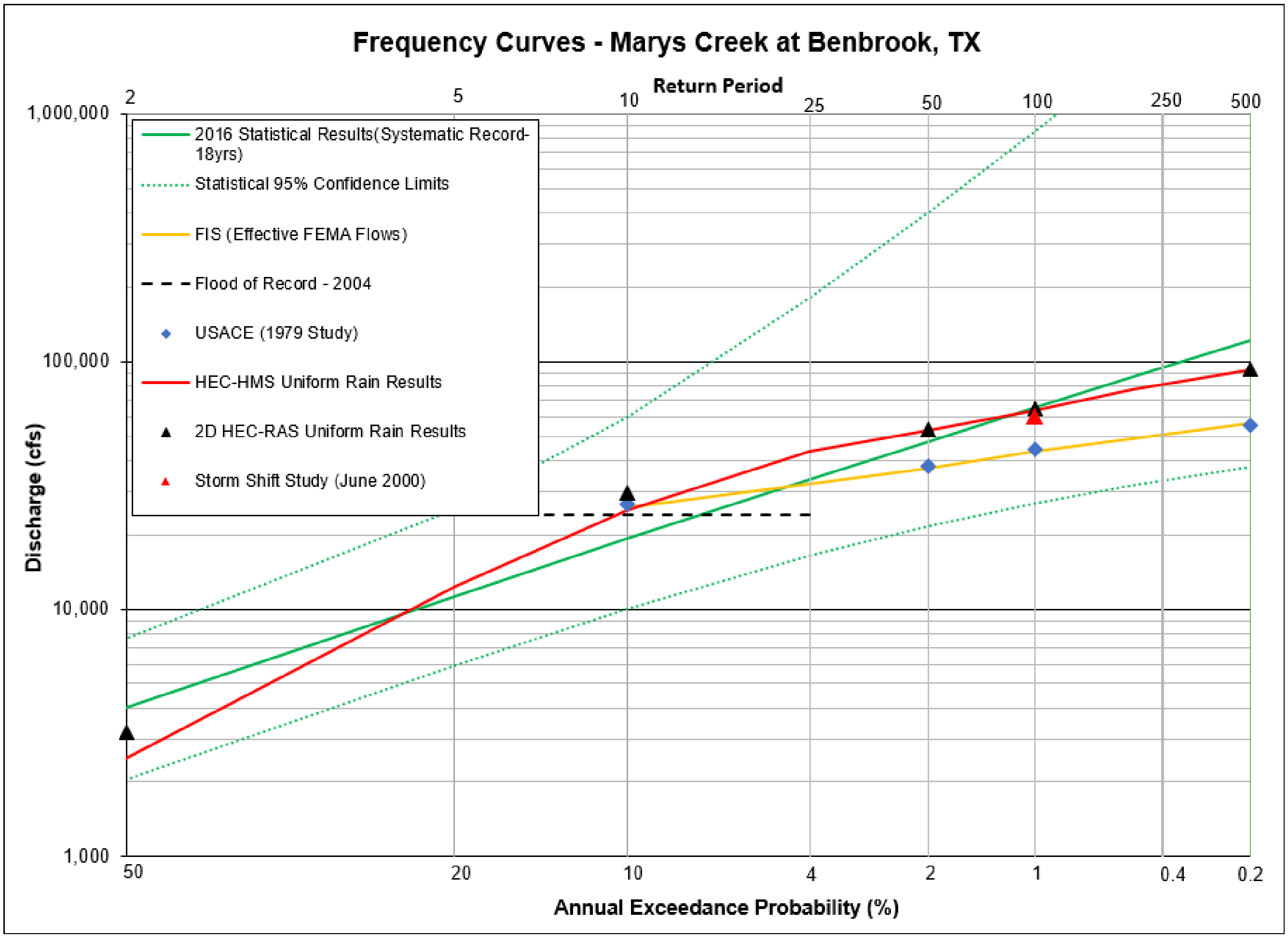


Figure 10.16: Flow Frequency Curve Comparison for Marys Creek at Benbrook Gage

Table 10.13: Comparison of Frequency Flows at Clear Fork Trinity River at Fort Worth Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	46,000	55,400	46,000	27,200	31,600	99,400	82,300	
0.004	200				25,200	27,500	83,800	73,000	
0.01	100	29,800	39,600	29,800	23,500	24,400	72,100	64,000	
0.02	50	24,600	32,600	24,600	21,500	21,400	62,600	55,100	
0.04	25		25,700	19,100	19,300	17,300	53,200	46,900	
0.1	10	13,800	18,100	13,800	16,000	14,200	31,500	29,100	
0.2	5			10,600	12,900	11,100	17,000	18,200	
0.5	2			7,100	7,900	6,600	5,700	7,600	

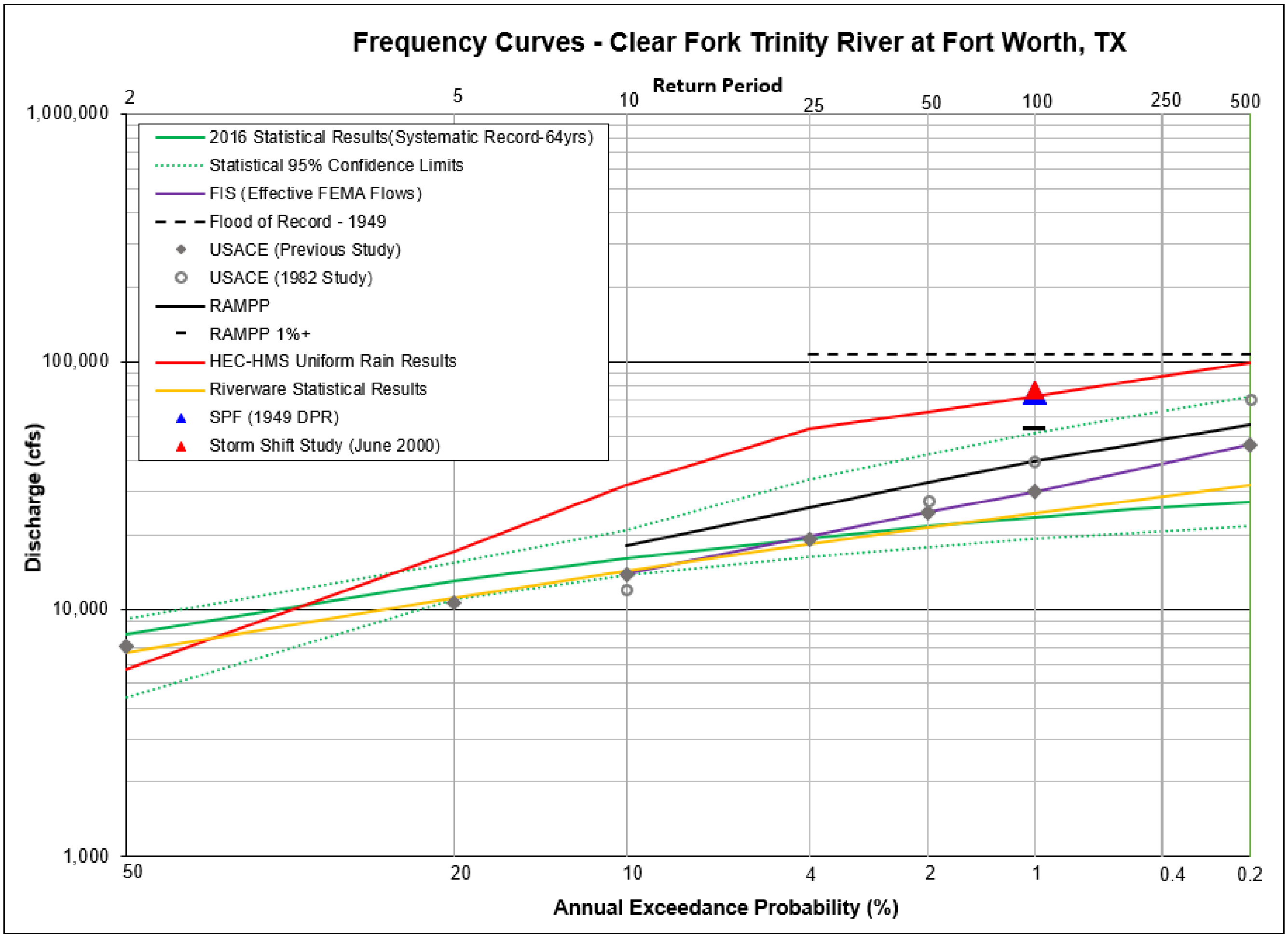


Figure 10.17: Flow Frequency Curve Comparison for Clear Fork Trinity River at Fort Worth Gage

Figure 10.18 below provides a comparison between the 100-year calibrated rainfall-runoff model (HEC-HMS) results, observed annual peak flows, 100-year USGS regression equation results, and 100-year statistical hydrology results the the Clear Fork at Fort Worth USGS gage. The statistical hydrology results show how the 100-year statistical hydrology value has changed as each additional annual peak flow is added to the record. Generally, at least 300-400 years of record are needed before the 1% annual chance (100-yr) flow frequency estimates will stop significantly changing over time with additional years of record, unless additional information such as rainfall-runoff modeling estimates are utilized in the statistical analysis. Because of this, flood frequency estimates have the possibility of being very different in the future than what they are today, even with 60+ years of record, as is available for this gage.

For this location, the HEC-HMS results are significantly higher than the statistical hydrology estimate as the statistical hydrology result has changed over time. The HEC-HMS results are also higher than the statistical hydrology 95% confidence limits. The HEC-HMS results are also higher than the USGS regression equation value, which considers the drainage area below USACE dams.and other major reservoirs.

Because of the differences in results at this location, additional investigation was perfomed to help understand the differences. An alternate statistical hydrology analysis was performed to test the sensitivity of the statistical hydrology results. The first part of the sensitivity test was using the May 1949 rainfall to add an additional year of record. The May 1949 rainfall event was simulated in the HEC-HMS model to develop an estimate of what kind of flood would result if the rainfall event occurred immediately after the construction of Benbrook dam instead of immediately before construction of the dam. Using the 1949 estimated losses and rainfall as identified in the USACE Fort Worth Floodway Detailed Project Report (DPR), this resulted in a peak flow of approximately 40,000 cfs at the Clear Fork at Fort Worth gage with current land use conditions and with Benbrook Dam in operation. This simulated 1949 peak flow is almost double the highest observed peak flow since Benbrook Dam was constructed.

The second part of the sensitivity test was replacing the observed 2000 peak flow (19,800 cfs) with the peak flow that was simulated in HEC-HMS by shifting the 2000 storm 15 miles over the Mary's Creek watershed. The HEC-HMS results for the Clear Fork at Fort Worth are heavily influenced by the Mary's Creek watershed, as Benbrook Dam controls a large portion of the rest of the drainage area, Details about the shifted storm is included in the previous discussion comparing results for the Mary's Creek at Benbrook gage. The resulting peak flow of the shifted storm at the Clear Fork at Fort Worth gage was 77,000 cfs, which is more than 3.5 times higher that the highest observed peak flow since Benbrook Dam was constructed. The results of the sensitivity test indicated that the statistical hydrology results and confidence limits are very sensitive to the occurrence of large events which came very close to happening in the watershed. The statistical hydrology upper confidence limit nearly doubled by including the storms from the sensitivity analysis. The results of the sensitivity test suggest the statistical hydrology 100-yr estimates and confidence limits could change significantly if large storm events are added to the record. The HEC-HMS results fall within the confidence limits of the alternate statistical hydrology analysis.

Rainfall analysis was also performed on the May 1990 event as well as the 2000 shifted storm event. The May 1990 event produced the largest observed peak flow at this gage since the construction of Benbrook Dam circa 1952. While this is the largest peak flow (20,900 cfs) this location has experienced, only about 3.8 inches of rain fell in 24-hours to produce that peak flow. This equates to about a 5-year rainfall event and is also consistent with the fact that observed annual peak flows have nearly matched this maximum valuue many times since the construction of Benbrook dam. The 2000 shifted storm over Mary's Creek would have resulted in a peak flow of about 77,000 cfs, from about 8.5 inches of rain in 24-hours. The 100-yr peak flow from HEC-HMS is 72,100 cfs, resulting from a NOAA Atlas 14 storm event with a 24-hour total of 8.6 inches, which is very similar to the rainfall amount from the shifted storm.

The watershed above this location and below Benbrook dam has not experienced a widespread rainfall event that would be similar to the 100-year 24-hour storm event relied upon for floodplain management. As a result, the current statistical hydrology results could be drastically underestimating the magnitude of the 100-yr flood at this location. The HEC-HMS modeling results are very important in understanding the potential flood hazard for this location because of the model's ability to simulate the watershed's response to a large (100-yr) rainfall event, which to date has not been experienced over this watershed.

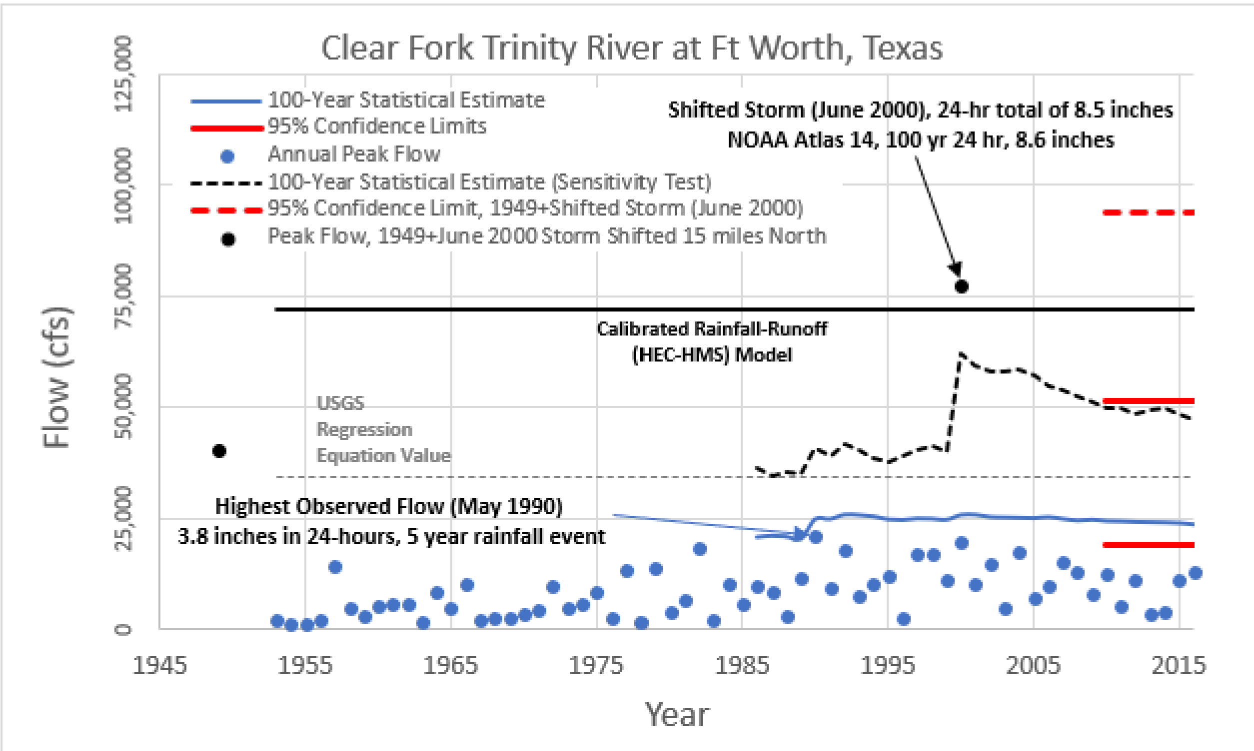


Figure 10.18 100-YR Flow Comparison for Clear Fork at Fort Worth Gage

Table 10.14: Comparison of Frequency Flows at West Fork Trinity River at Fort Worth Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	77,900	93,000	77,900	62,100	53,300	113,400	100,000	
0.004	200				52,100	44,300	92,900	86,400	
0.01	100	47,000	56,300	47,000	44,900	38,000	80,500	75,200	
0.02	50	35,700	47,000	35,700	37,900	32,100	68,600	64,300	
0.04	25		37,000	26,900	31,300	24,900	57,400	54,300	
0.1	10	18,900	24,800	18,900	23,000	19,800	35,600	36,600	
0.2	5			13,800	17,000	15,000	19,900	23,600	
0.5	2			9,400	9,200	8,800	7,300	10,700	

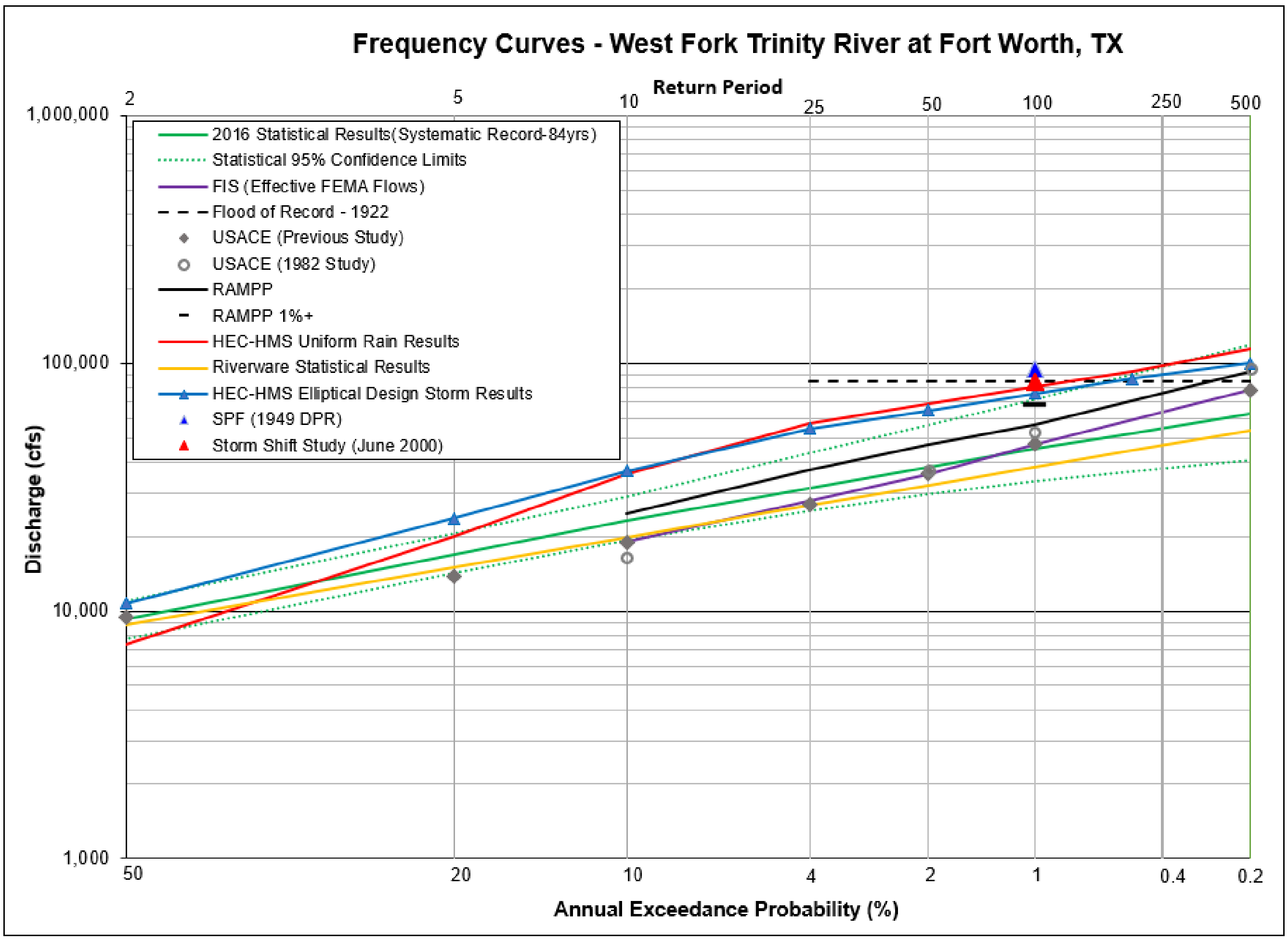


Figure 10.19: Flow Frequency Curve Comparison for West Fork Trinity River at Fort Worth Gage

Figure 10.20 below provides a comparison between the 100-year calibrated rainfall-runoff model (HEC-HMS) results, observed annual peak flows, 100-year USGS regression equation results, and 100-year statistical hydrology results at the West Fork Trinity River at Fort Worth USGS gage. The statistical hydrology results show how the 100-year statistical hydrology value has changed as each additional annual peak flow is added to the record. Generally, at least 300-400 years of record are needed before the 1% annual chance (100-yr) flow frequency estimates will stop significantly changing over time with additional years of record, unless additional information such as rainfall-runoff modeling estimates are utilized in the statistical analysis.

For this location, the HEC-HMS results have been both higher and lower than the statistical hydrology estimate as the statistical hydrology result has changed over time. The HEC-HMS results are higher than the current statistical hydrology 95% confidence limits and are higher than the statistical hydrology estimate using the full record length. The HEC-HMS results are higher than the USGS regression equation value, which considers the drainage area below USACE reservoirs and other major reservoirs.Because of the differences in results at this location, additional investigation was perfomed to help understand the differences. The HEC-HMS results for the West Fork at Fort Worth gage continue to be heavily influenced by flows from Mary's Creek and the Clear Fork. The peak flow resulting from shifting the 2000 storm 15 miles over the Mary's Creek watershed was included in the plot of results as an additional point of comparison against a flood event that came very close to happening. Details about the shifted storm is included in the previous discussion comparing results for the Mary's Creek at Benbrook gage.

Rainfall analysis was also performed on the May 1990 event as well as the 2000 shifted storm event. The May 1990 event produced the largest peak flow at this gage since the construction of Benbrook Dam circa 1952. While this is the largest peak flow (36,200 cfs) this location has experienced, only about 3.6 inches of rain fell in 24-hours to produce that peak flow. This equates to between a 2-year to 5-year rainfall event. The 2000 shifted storm over Mary's Creek would have resulted in a peak flow of about 84,000 cfs, from about 7.9 inches of rain in 24-hours. The 100-yr peak flow from HEC-HMS is 75,200 cfs and results from a NOAA Atlas 14 storm event with a 24-hour total of 8.2 inches, which is similar to the rainfall amount from the 2000 shifted storm.

The watershed above this location and below Benbrook dam and Lake Worth has not experienced a widespread rainfall event that would be similar to the 100-year 24-hour event relied upon for floodplain management. The HEC-HMS modeling results are very important in understanding the potential flood hazard for this location because of the models ability to simulate the watershed's response to a large (100-yr) rainfall event, which to date has not been experienced over this watershed.

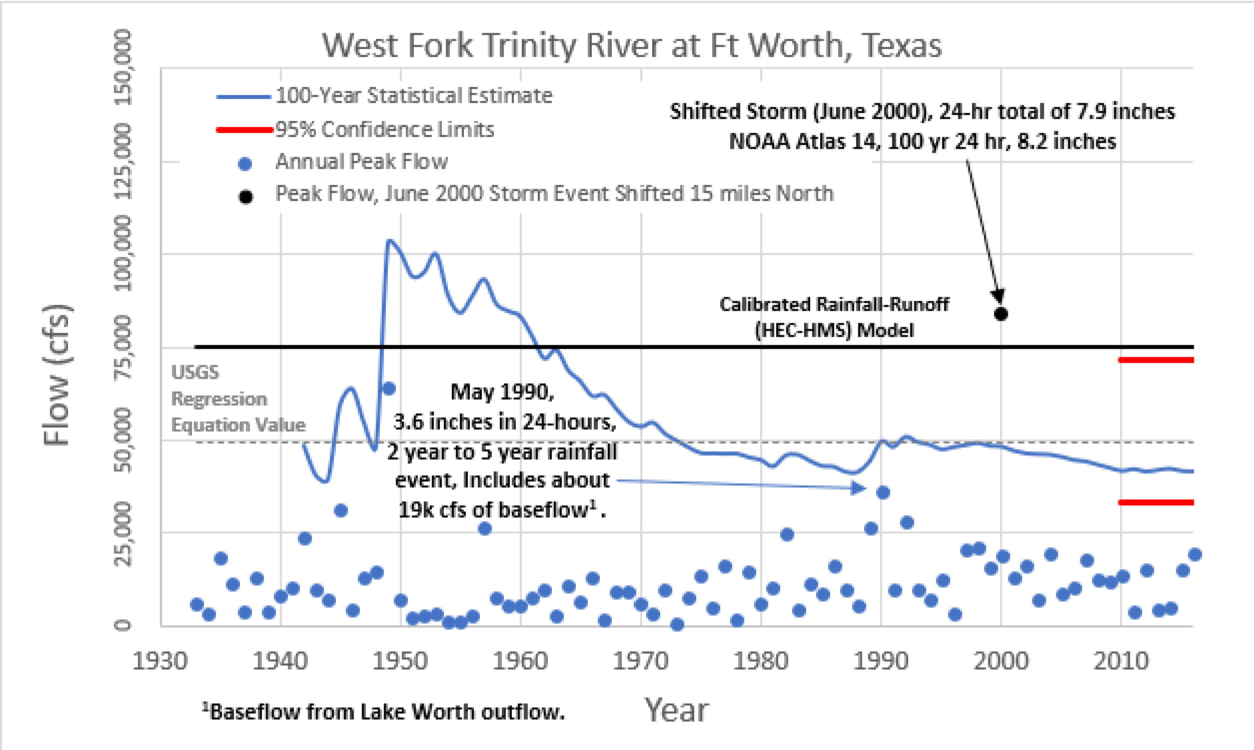


Figure 10.20 100-YR Flow Comparison for the West Fork Trinity River at Fort Worth Gage

Table 10.15: Comparison of Frequency Flows at West Fork Trinity River at Beach St Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	110,400		110,400	76,000		119,400	108,400	
0.004	200				63,200		97,500	90,400	
0.01	100	71,700		71,700	54,200		82,300	77,200	
0.02	50	60,500		60,500	45,700		69,400	66,700	
0.04	25			47,400	37,800		58,200	56,100	
0.1	10	33,800		33,800	28,000		34,500	36,900	
0.2	5			24,800	21,000		19,700	23,700	
0.5	2			13,200	12,000		8,600	11,500	

Figure 10.21: Flow Frequency Curve Comparison for West Fork Trinity River at Beach St Gage

Table 10.16: Comparison of Frequency Flows at Big Fossil Creek at Haltom City Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	42,100		53,000	46,300				
0.004	200				40,300				
0.01	100	33,800		40,000	35,600				
0.02	50	29,200		35,100	30,900				
0.04	25			30,300	26,000				
0.1	10	20,300		24,100	19,500				
0.2	5				14,400				
0.5	2			12,700	7,400				

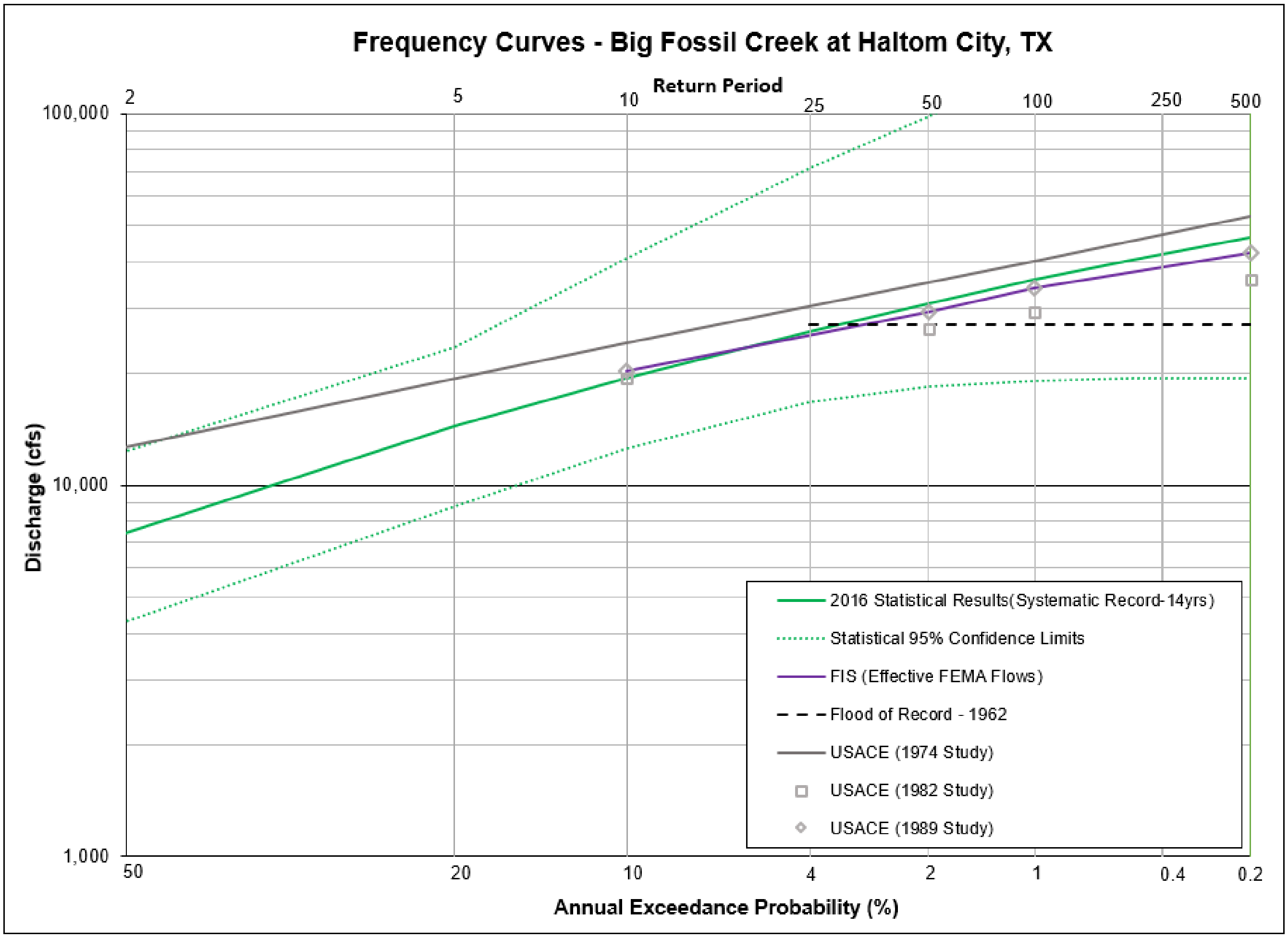


Figure 10.22: Flow Frequency Curve Comparison for Big Fossil Creek at Haltom City Gage

For Village Creek at Everman, the HEC-HMS results are lower than previous studies in the watershed but significantly higher, and even outside of the confidence limits of the statistical hydrology results based on 27 years of systematic record. With less than 30-years of systematic record, there is a large amount of uncertainty in estimates more rare than the 10-yr recurrence interval (Section 5.3). The confidence in the statistical hydrology results for events more rare than the 10-yr recurrence interval is further weakened by the flatness of the frequency curve. For example, the difference between the 10% annual chance (10-yr) event and the 0.2% (500-yr) annual chance event is only 30% (13,600 cfs vs 17,300 cfs). Every other non-regulated location within the Trinity Watershed has a difference of more than 100% (median of more than 250%) between the same 2 events, based on the final flow recommendations in Section 11. The difference in HEC-HMS results between the same 2 events is 170% (20,200 cfs vs 54,800 cfs), which is more consistent with the rest of the results in the Trinity River Basin.

The rating curve is also questionable for flows larger than 10,100 cfs as there is no USGS flow measurement larger than this, and several other measurements near or below this value are rated by the USGS as “poor”. While peak flows above 10,000 cfs are questionable for this gage, the HEC-HMS model was able to replicate the general shape and timing of the observed storm events. Because of this, the HEC-HMS results for this location are likely more reliable than the higher values developed during previous studies from 1970 and 1985.

Table 10.17: Comparison of Frequency Flows at Village Creek at Everman Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500			96,000	17,300		54,800		
0.004	200				17,000		46,100		
0.01	100			70,000	16,600		39,700		
0.02	50			59,000	16,000		33,000		
0.04	25			50,000	15,200		27,200		
0.1	10			38,000	13,600		20,200		
0.2	5				11,800		14,300		
0.5	2				7,700		7,400		

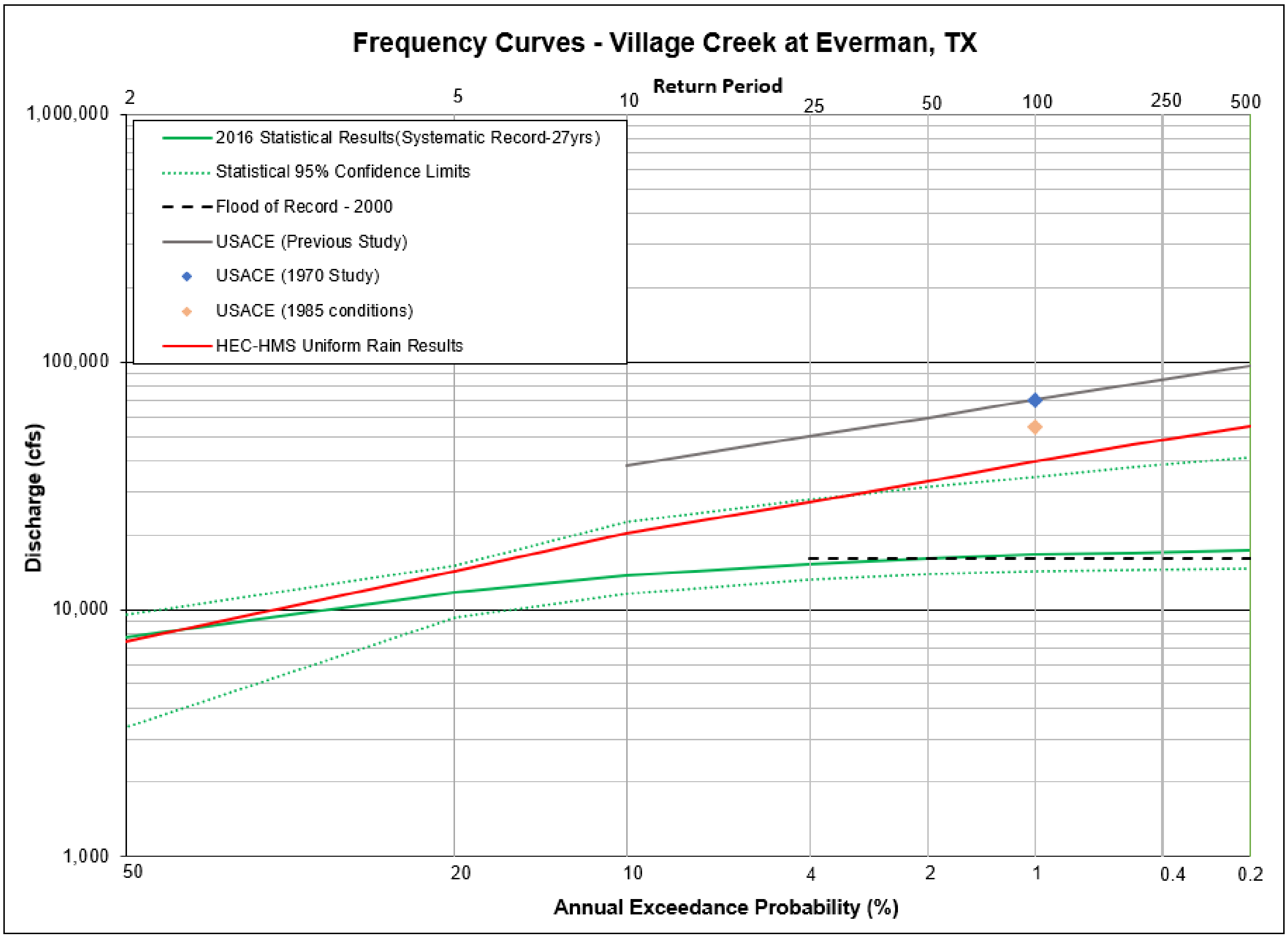


Figure 10.23: Flow Frequency Curve Comparison for Village Creek at Everman Gage

Table 10.18: Comparison of Frequency Flows for Lake Arlington Outflow

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	49,700		45,600			37,500		
0.004	200						26,800		
0.01	100	25,000		27,700			18,700		
0.02	50	16,500		20,500			10,500		
0.04	25			13,400			4,900		
0.1	10	3,400		7,900			3,600		
0.2	5						3,500		
0.5	2						2,300		

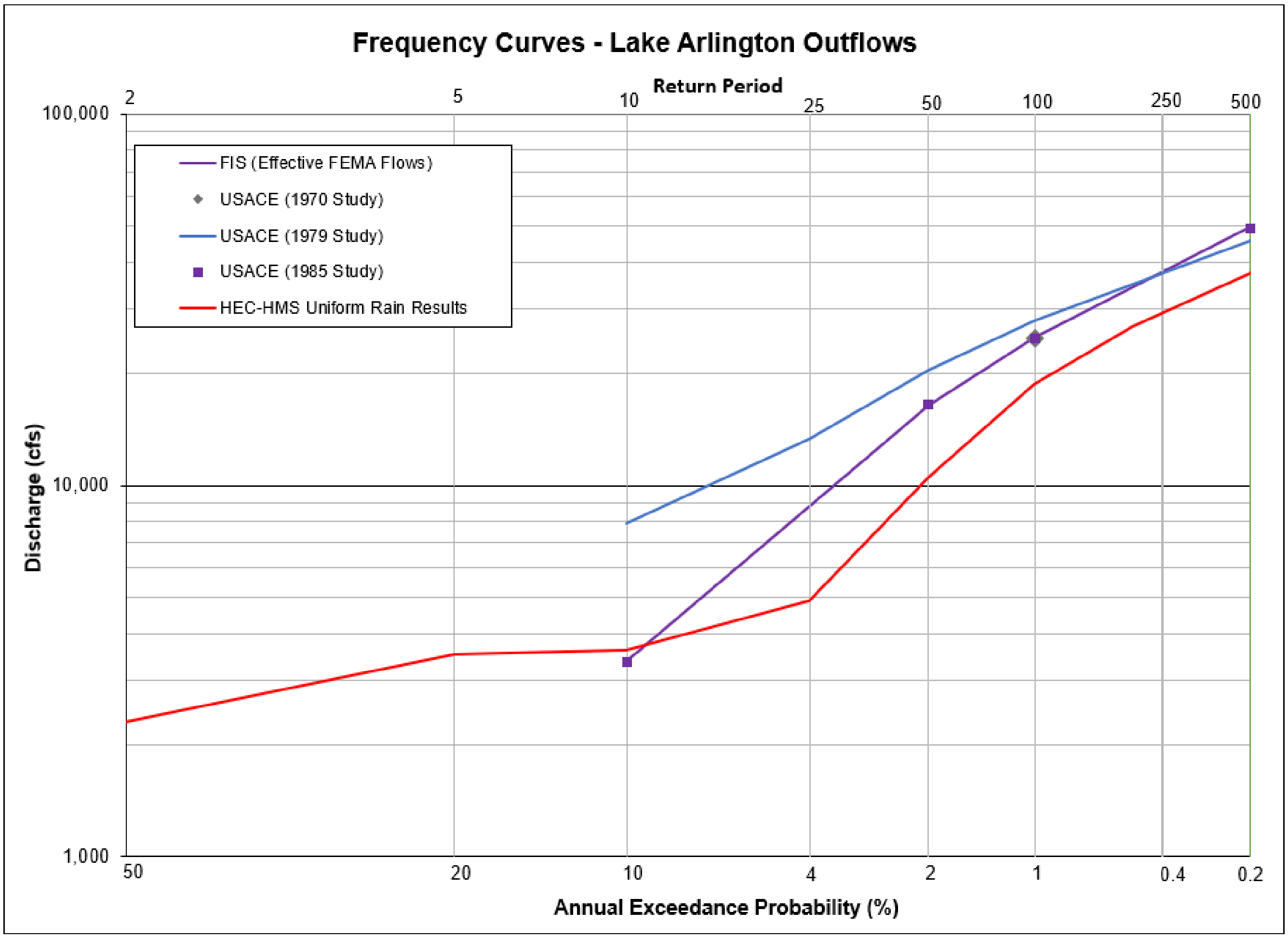


Figure 10.24: Flow Frequency Curve Comparison for Lake Arlington Outflow

Table 10.19: Comparison of Frequency Flows at West Fork Trinity River at Grand Prairie Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	160,500	150,800	149,800	108,200	100,300	146,400	128,100	
0.004	200				81,400	74,000	113,800	96,500	
0.01	100	90,000	92,000	86,100	64,600	58,100	88,200	78,000	
0.02	50	69,400	72,500	65,000	50,500	45,000	65,700	58,400	
0.04	25		56,900	49,900	38,700	31,200	49,300	44,200	
0.1	10	35,800	34,900	33,300	26,000	22,900	26,500	27,100	
0.2	5			25,100	18,100	16,100	17,700	17,200	
0.5	2			14,300	9,500	8,700	9,000	8,500	

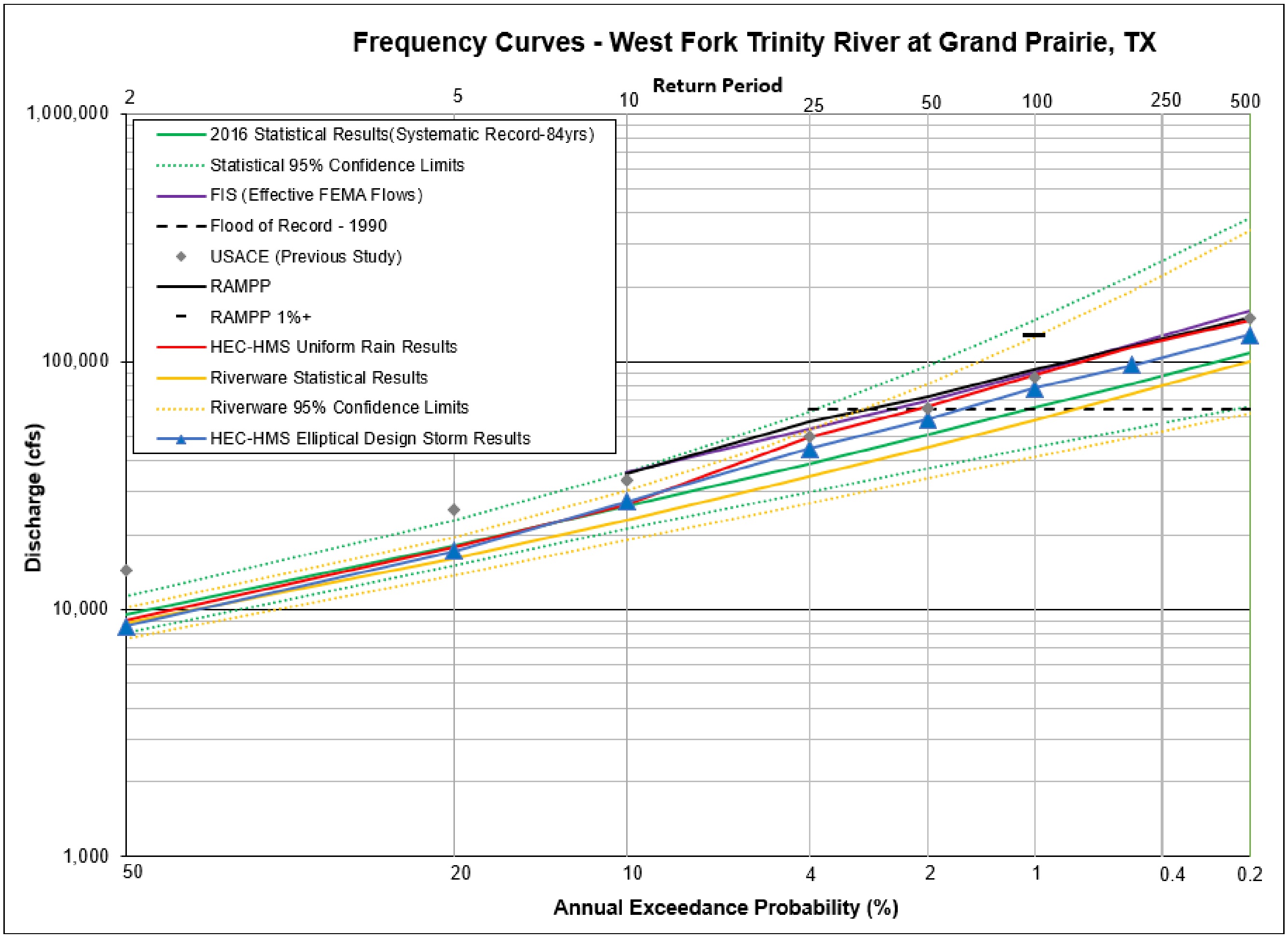


Figure 10.25: Flow Frequency Curve Comparison for West Fork Trinity River at Grand Prairie Gage

Figure 10.26 below provides a comparison between the 100-year calibrated rainfall-runoff model (HEC-HMS) results, observed annual peak flows, 100-year USGS regression equation results, and 100-year statistical hydrology results at the West Fork Trinity River at Grand Praire USGS gage. The statistical hydrology results show how the 100-year statistical hydrology value has changed as each additional annual peak flow is added to the record. Generally, at least 300-400 years of record are needed before the 1% annual chance (100-yr) flow frequency estimates will stop significantly changing over time with additional years of record, unless additional information such as rainfall-runoff modeling estimates are utilized in the statistical analysis.

For this location, the HEC-HMS results have been both higher and lower than the statistical hydrology estimate as the statistical hydrology result has changed over time. The HEC-HMS results are well within the statistical hydrology 95% confidence limits and are higher than the statistical hydrology estimate using the full record length. The HEC-HMS results are lower than the USGS regression equation value, which considers the drainage area below USACE reservoirs and other major reservoirs.

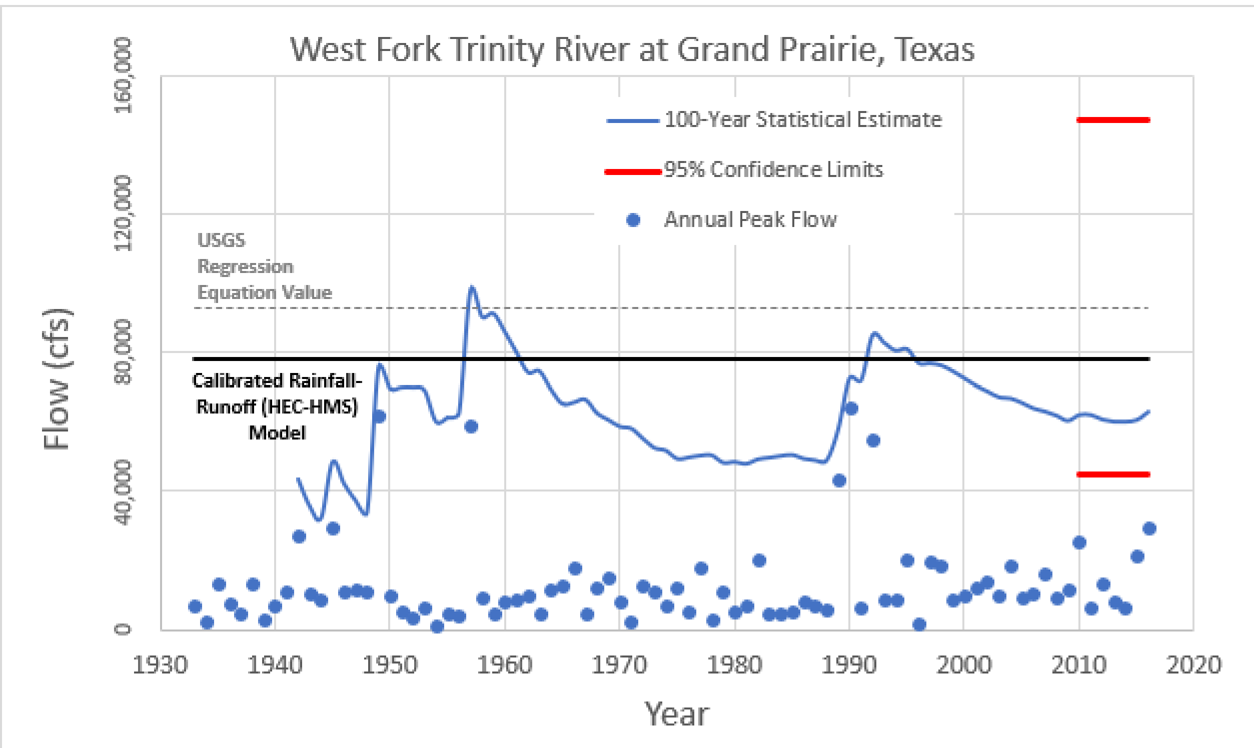


Figure 10.26 100-YR Flow Comparison for West Fork Trinity River at Grand Praire Gage

Table 10.20: Comparison of Frequency Flows at Mountain Creek near Venus Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				28,800		22,300		
0.004	200				22,900		18,900		
0.01	100				18,900		16,500		
0.02	50				15,400		13,900		
0.04	25				12,200		11,600		
0.1	10				8,500		8,800		
0.2	5				6,000		6,700		
0.5	2				3,100		3,600		

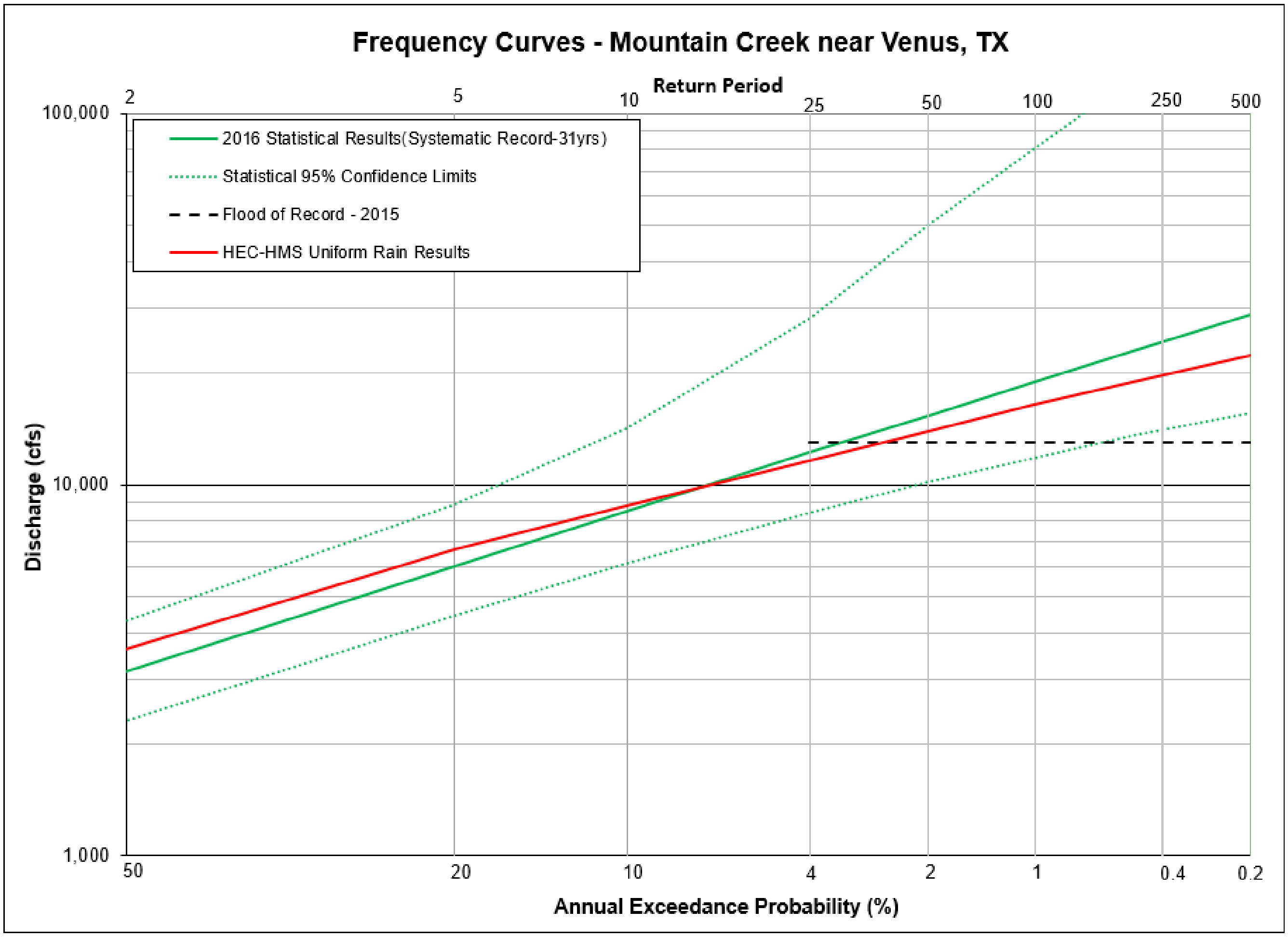


Figure 10.27: Flow Frequency Curve Comparison for Mountain Creek near Venus Gage

Table 10.21: Comparison of Frequency Flows at Walnut Creek near Mansfield Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	39,000		39,000	31,600		35,100		
0.004	200				25,700		29,800		
0.01	100	28,300		28,300	21,600		25,300		
0.02	50	23,100		23,100	17,800		20,900		
0.04	25				14,300		17,100		
0.1	10	14,300		14,300	10,100		11,600		
0.2	5				7,200		8,100		
0.5	2				3,700		4,100		

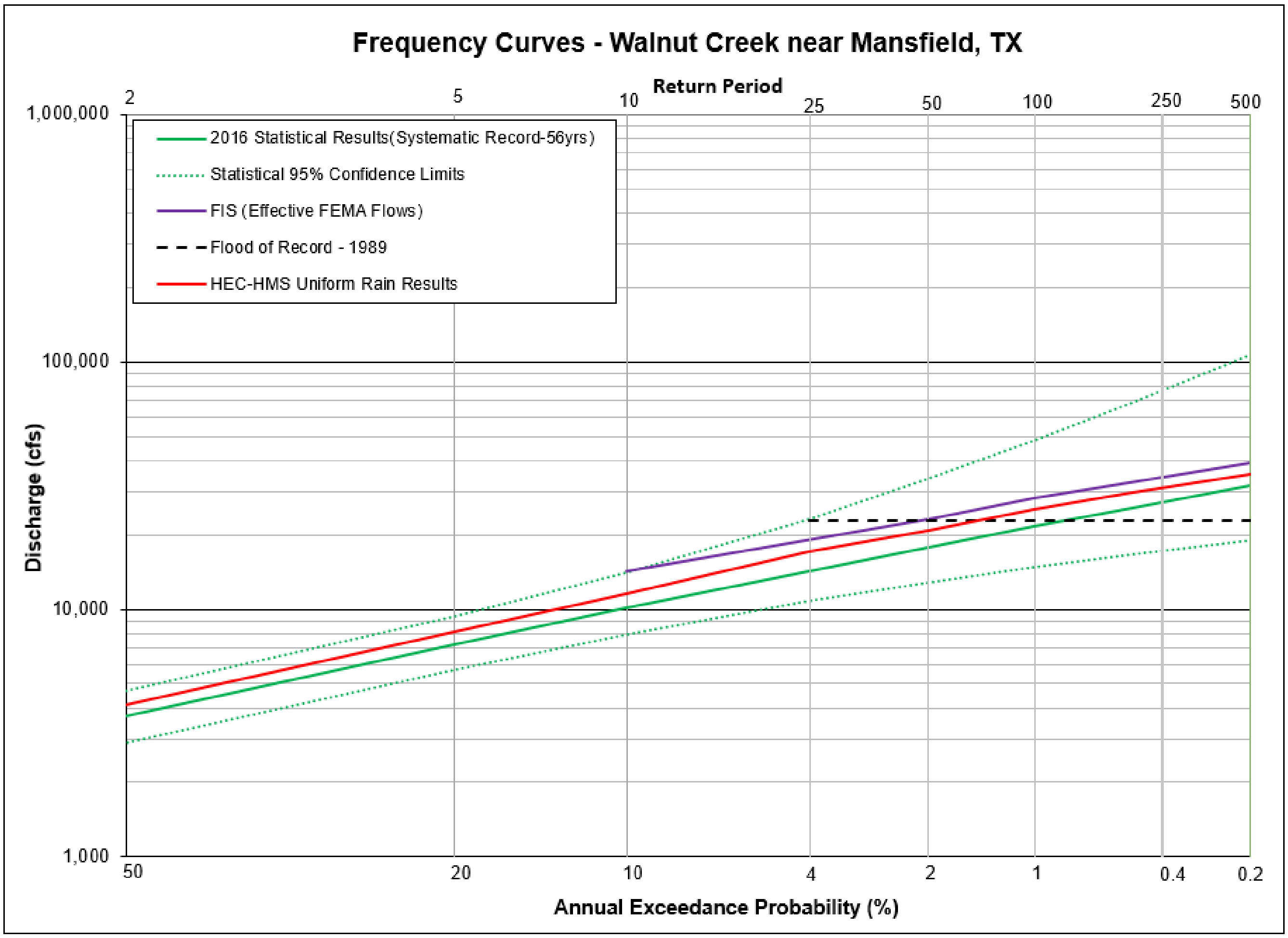


Figure 10.28: Flow Frequency Curve Comparison for Walnut Creek near Mansfield Gage

Figure 10.29 below provides a comparison between the 100-year calibrated rainfall-runoff model (HEC-HMS) results, observed annual peak flows, 100-year USGS regression equation results, and 100-year statistical hydrology results at the Walnut Creek near Mansfield USGS gage. The statistical hydrology results show how the 100-year statistical hydrology value has changed as each additional annual peak flow is added to the record. Generally, at least 300-400 years of record are needed before the 1% annual chance (100-yr) flow frequency estimates will stop significantly changing over time with additional years of record, unless additional information such as rainfall-runoff modeling estimates are utilized in the statistical analysis.

For this location, the HEC-HMS results have been both higher and lower than the statistical hydrology estimate as the statistical hydrology result has changed over time. The HEC-HMS results are well within the statistical hydrology 95% confidence limits and are similar to the statistical hydrology estimate using the full record length. The HEC-HMS results are higher than the USGS regression equation value, which considers the drainage area below USACE reservoirs and other major reservoirs, which has been exceeded previously.

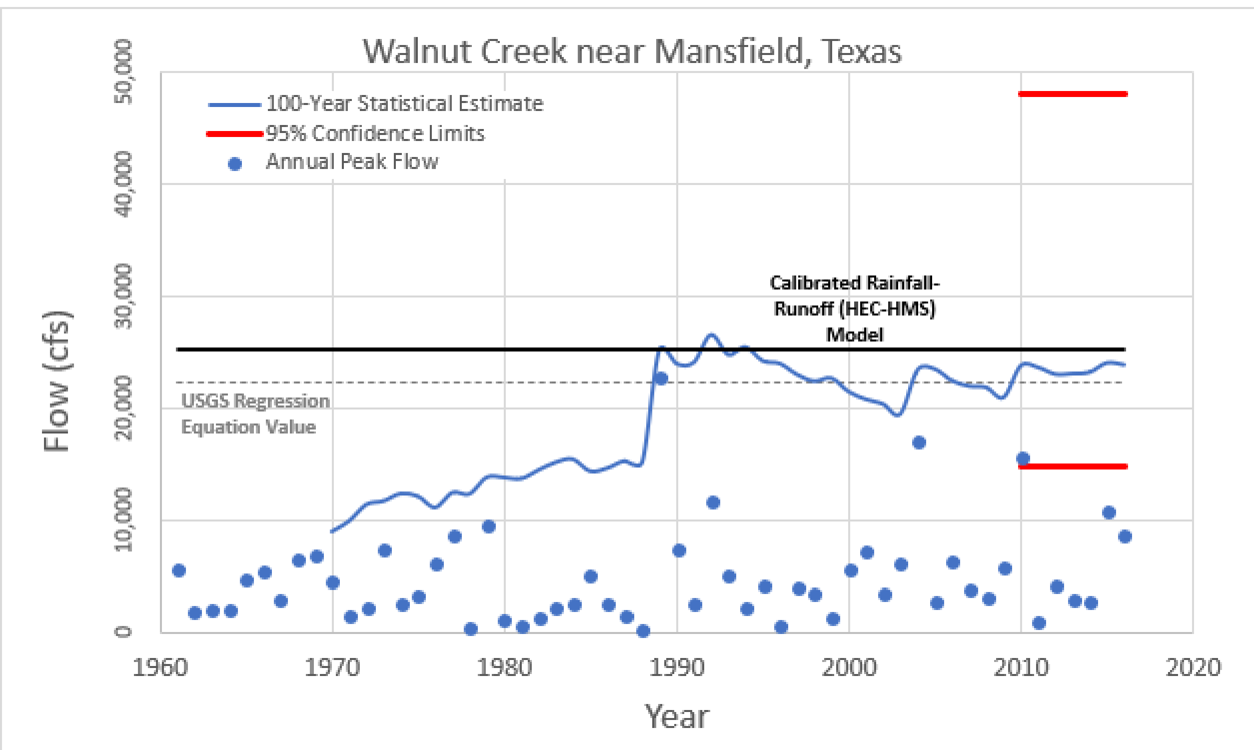


Figure 10.29 100-YR Flow Comparison for Walnut Creek near Mansfield Gage

Table 10.22: Comparison of Frequency Flows for Joe Pool Lake Outflow

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	103,800		103,800			0		4,000
0.004	200						0		4,000
0.01	100	74,700		74,700			0		4,000
0.02	50	59,400		59,400			0		4,000
0.04	25						0		4,000
0.1	10	34,100		34,100			0		4,000
0.2	5						0		2,400
0.5	2						0		1,200

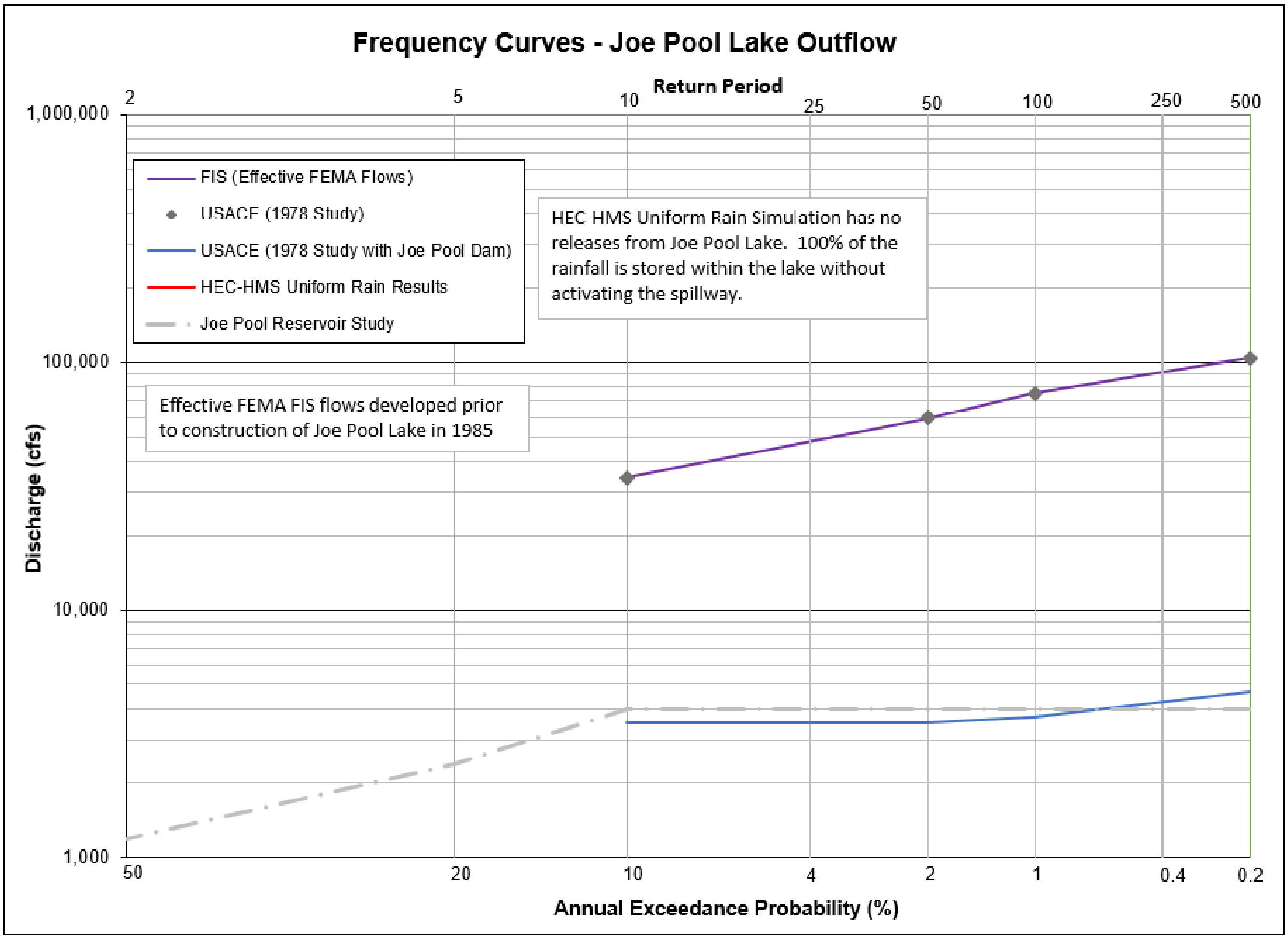


Figure 10.30: Flow Frequency Curve Comparison for Joe Pool Lake Outflow

Table 10.23: Comparison of Frequency Flows for Mountain Creek Lake Outflow

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	77,100		105,700			69,400		
0.004	200						63,800		
0.01	100	59,300		71,000			56,600		
0.02	50	51,000		52,300			48,000		
0.04	25						40,500		
0.1	10	33,500		32,800			29,700		
0.2	5						21,700		
0.5	2						11,900		

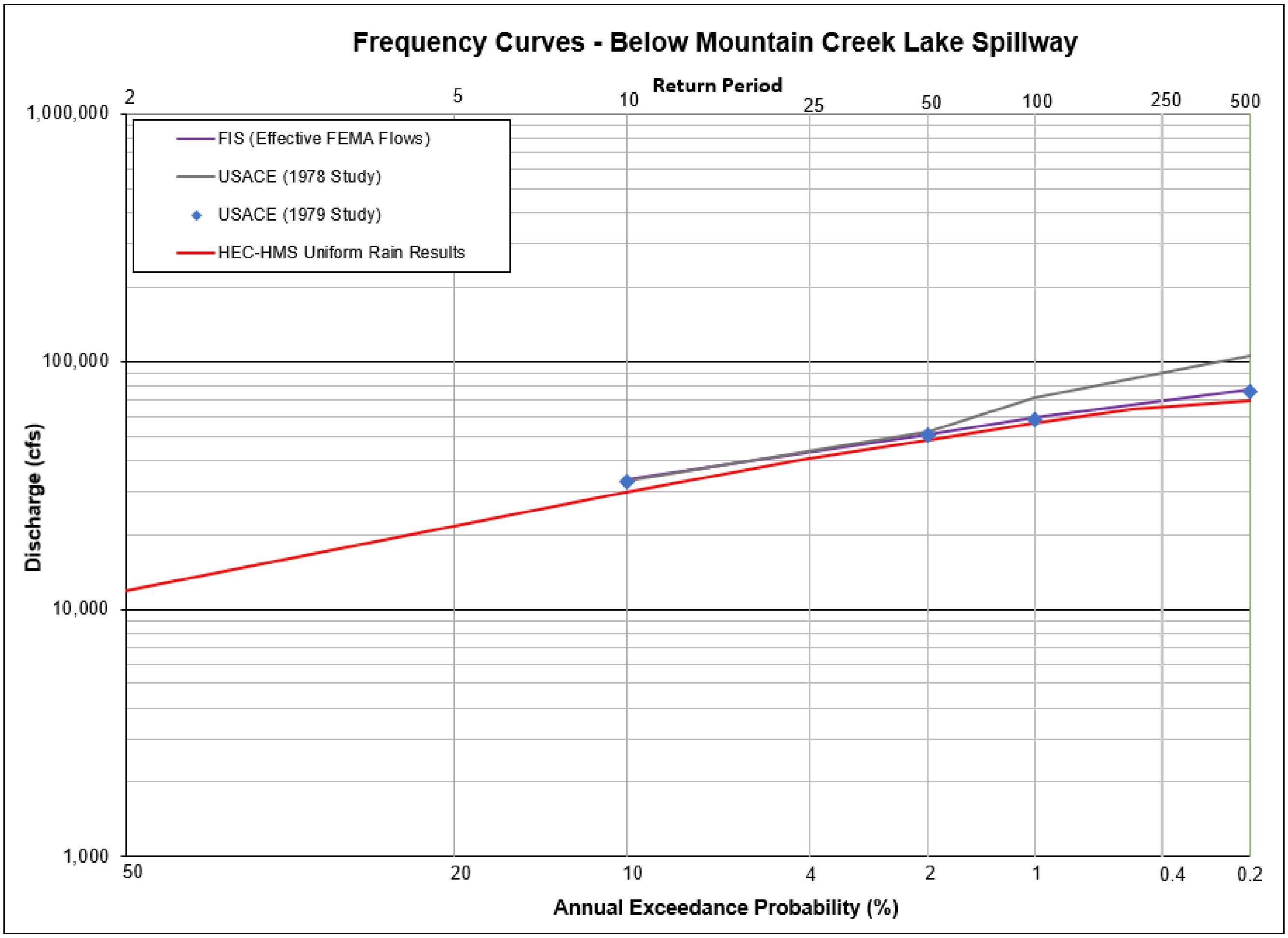


Figure 10.31: Flow Frequency Curve Comparison for Mountain Creek Lake Outflow

Table 10.24: Comparison of Frequency Flows at Mountain Creek at Grand Praire Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	62,600		93,700	24,100	19,700	52,600		
0.004	200				21,900	18,400	44,600		
0.01	100	48,100		67,000	20,200	17,300	38,300		
0.02	50	41,300		50,100	18,400	15,900	31,900		
0.04	25				16,700	13,700	26,700		
0.1	10	26,800		27,000	14,200	11,700	20,400		
0.2	5				12,200	9,200	15,500		
0.5	2				8,900	5,100	8,800		

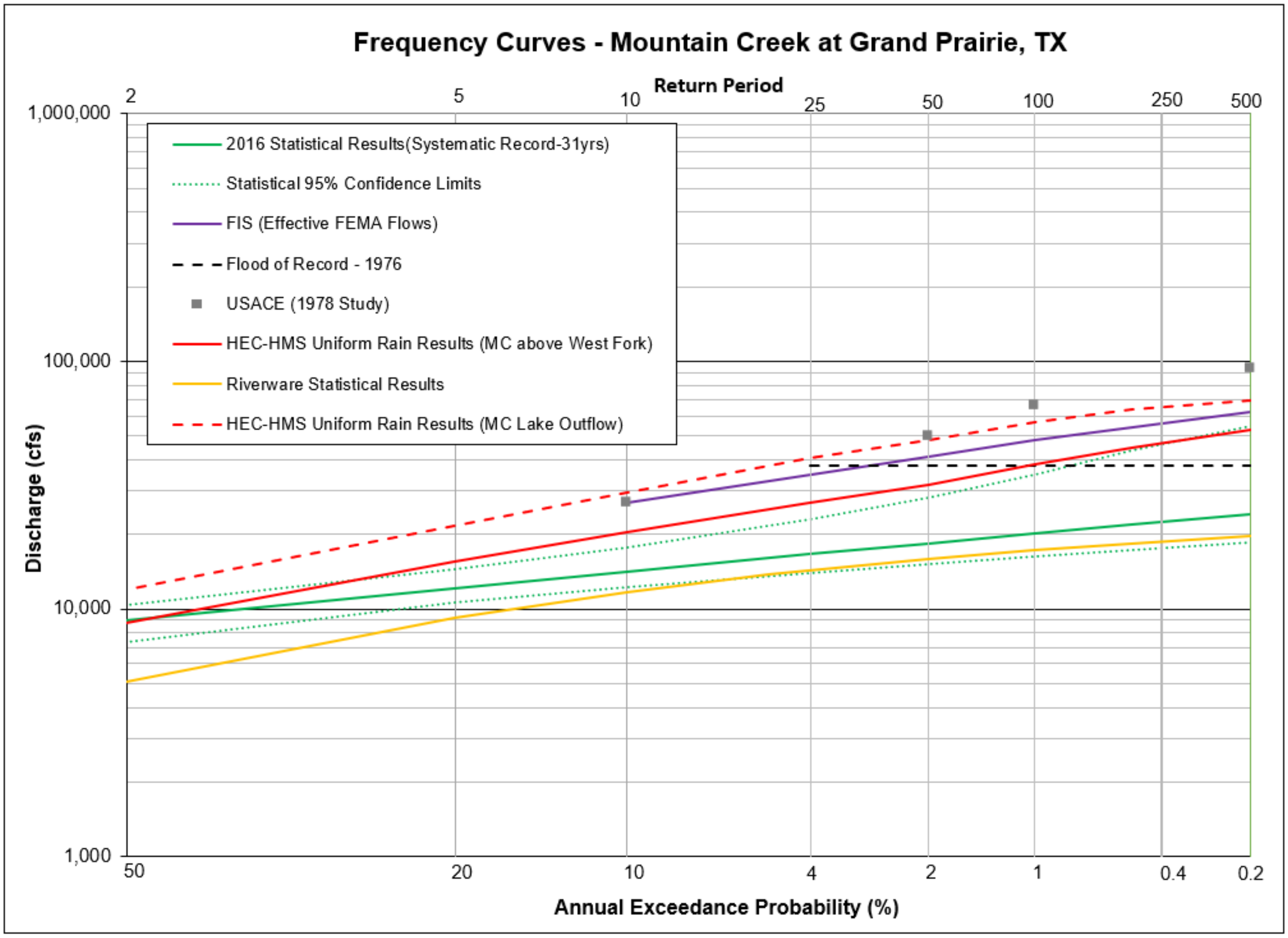


Figure 10.32: Flow Frequency Curve Comparison for Mountain Creek at Grand Prairie Gage

Table 10.25: Comparison of Frequency Flows at Elm Fork Trinity River at Gainesville Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	86,000			90,400		87,500		
0.004	200				70,100		71,900		
0.01	100	54,100			56,900		60,400		
0.02	50	43,400			45,400		48,400		
0.04	25				35,400		38,300		
0.1	10	22,400			24,200		26,500		
0.2	5				17,000		18,100		
0.5	2				8,700		8,300		

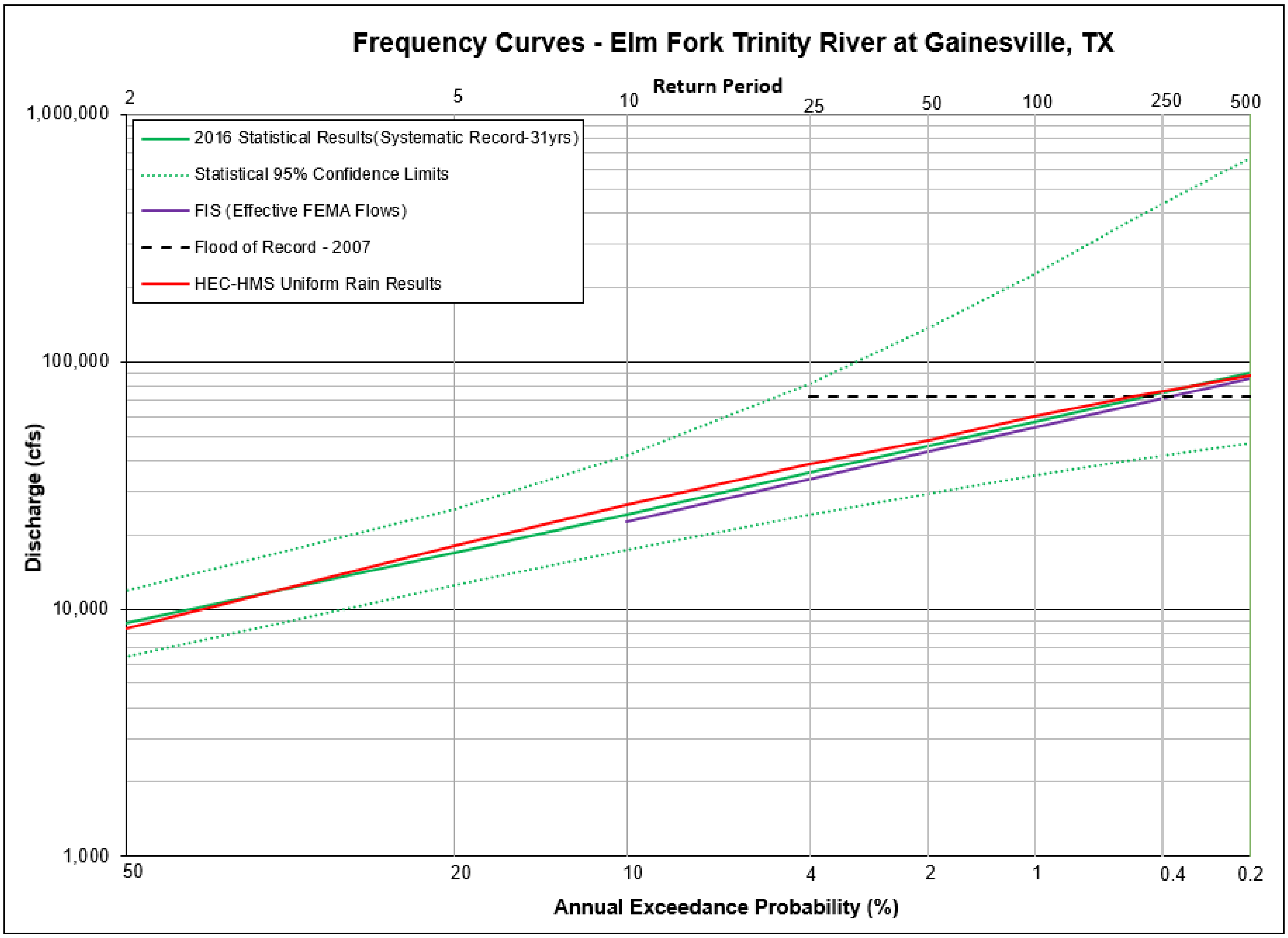


Figure 10.33: Flow Frequency Curve Comparison for Elm Fork Trinity River at Gainesville Gage

For Timber Creek near Collinsville, there is no existing FIS information or other previous study to compare to. The HEC-HMS results are lower than the statistical hydrology results based on 31 years of systematic record. With about 30 years of systematic record, there is a large amount of uncertainty in estimates more rare than the 10-yr recurrence interval (Section 5.3). The HEC-HMS results match up well with the 2007 event, which was the largest event on record. This event was very intense with a 6-hour basin average amount of about 6 inches with point rainfall totals in excess of 8 inches.

Table 10.26: Comparison of Frequency Flows at Timber Creek near Collinsville Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				78,600		30,500		
0.004	200				55,400		25,600		
0.01	100				41,000		22,000		
0.02	50				29,100		18,200		
0.04	25				19,600		14,900		
0.1	10				10,300		10,800		
0.2	5				5,400		7,500		
0.5	2				1,400		2,600		

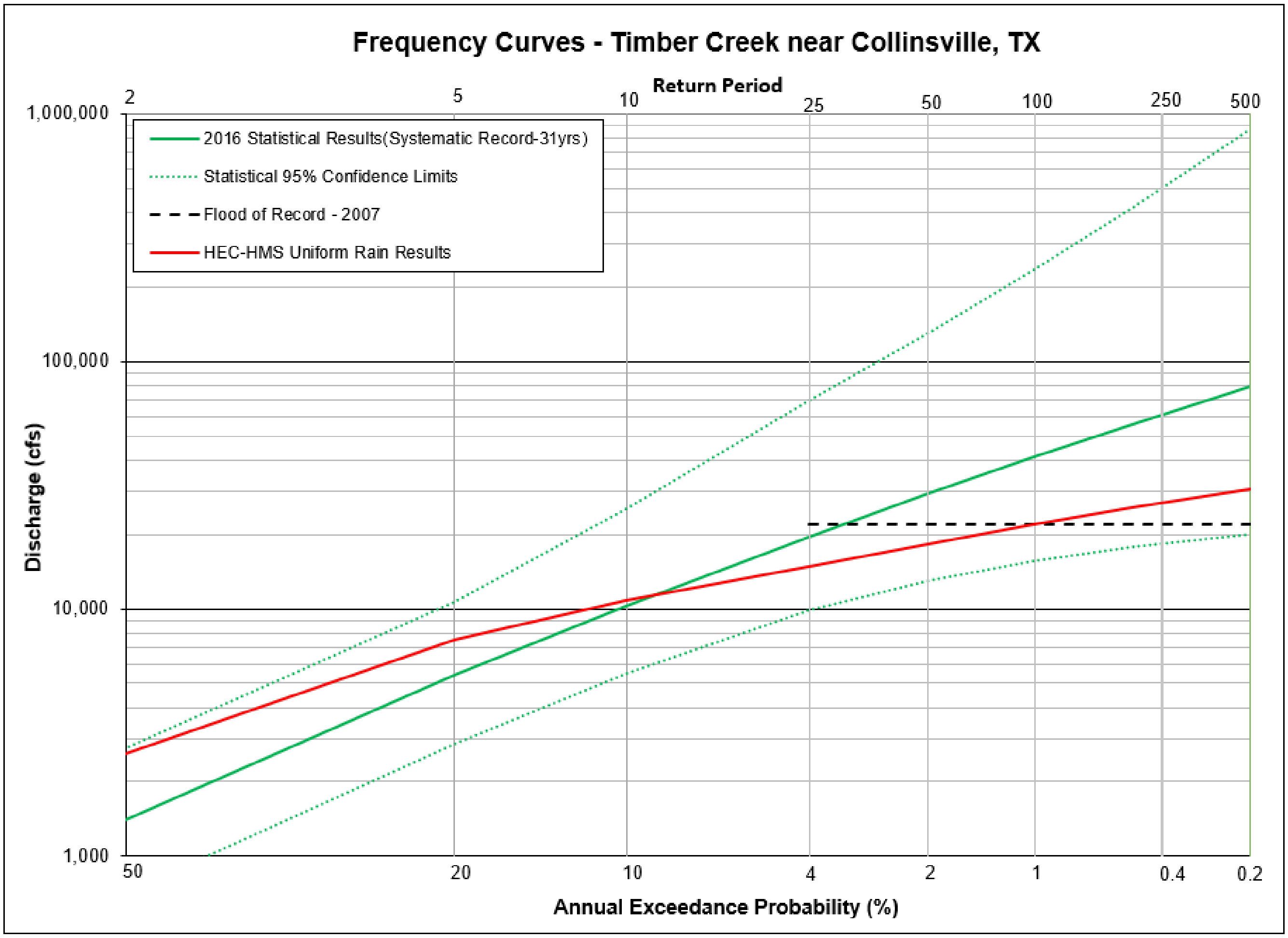


Figure 10.34: Flow Frequency Curve Comparison for Timber Creek near Collinsville Gage

Table 10.27: Comparison of Frequency Flows at Range Creek near Collinsville Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				72,000		36,700		
0.004	200				49,700		31,700		
0.01	100				36,700		28,000		
0.02	50				26,300		24,000		
0.04	25				18,300		20,400		
0.1	10				10,500		12,900		
0.2	5				6,200		8,300		
0.5	2				2,300		2,700		

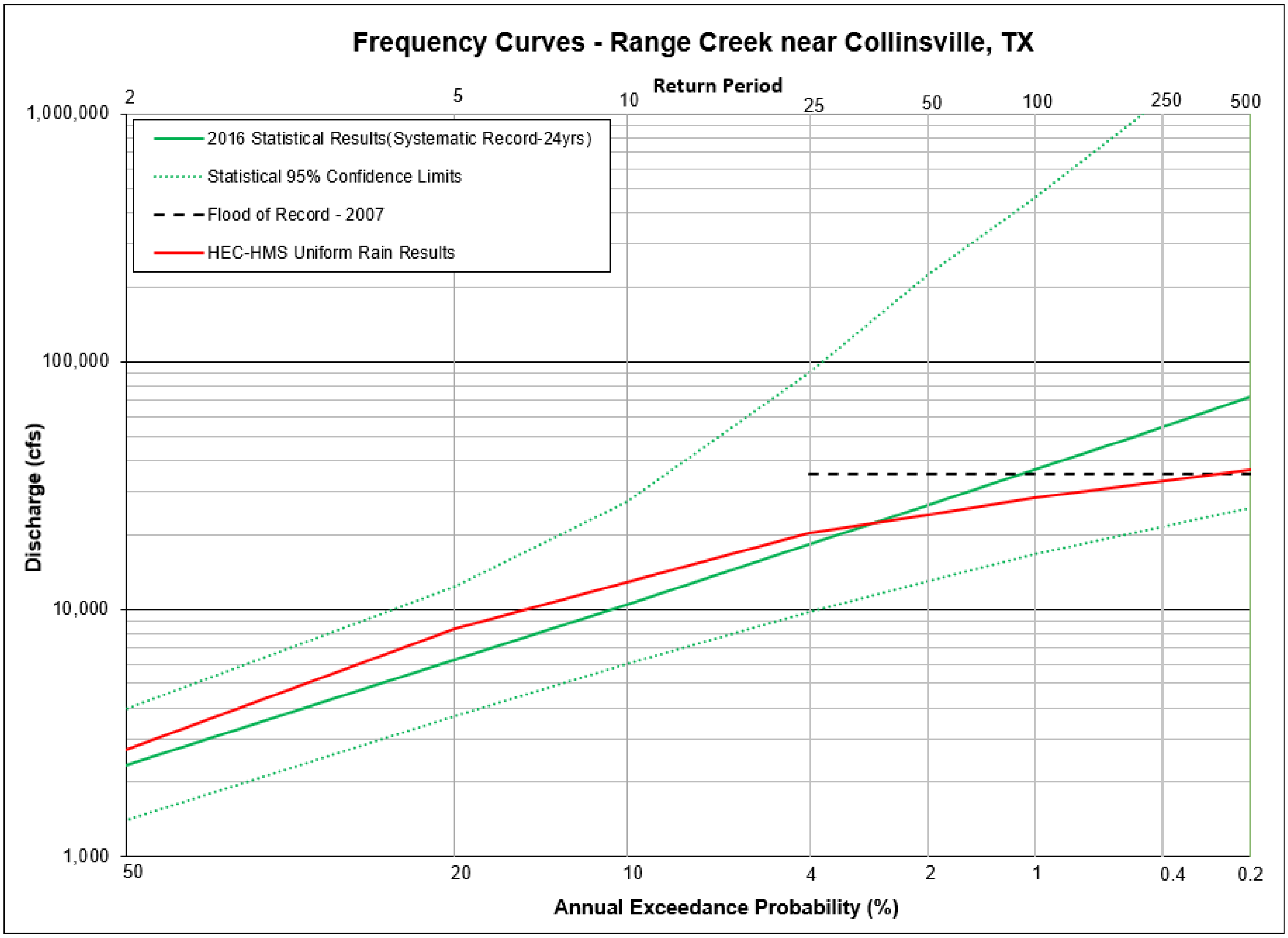


Figure 10.35: Flow Frequency Curve Comparison for Range Creek near Collinsville Gage

Table 10.28: Comparison of Frequency Flows for Ray Roberts Outflow

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500			6,300	212,700		3,200		7,000
0.004	200				114,500		2,000		7,000
0.01	100			6,100	69,000		1,100		7,000
0.02	50			6,000	39,900		210		7,000
0.04	25				21,800		0		7,000
0.1	10			6,000	8,700		0		7,000
0.2	5				3,700		0		4,000
0.5	2				740		0		2,000

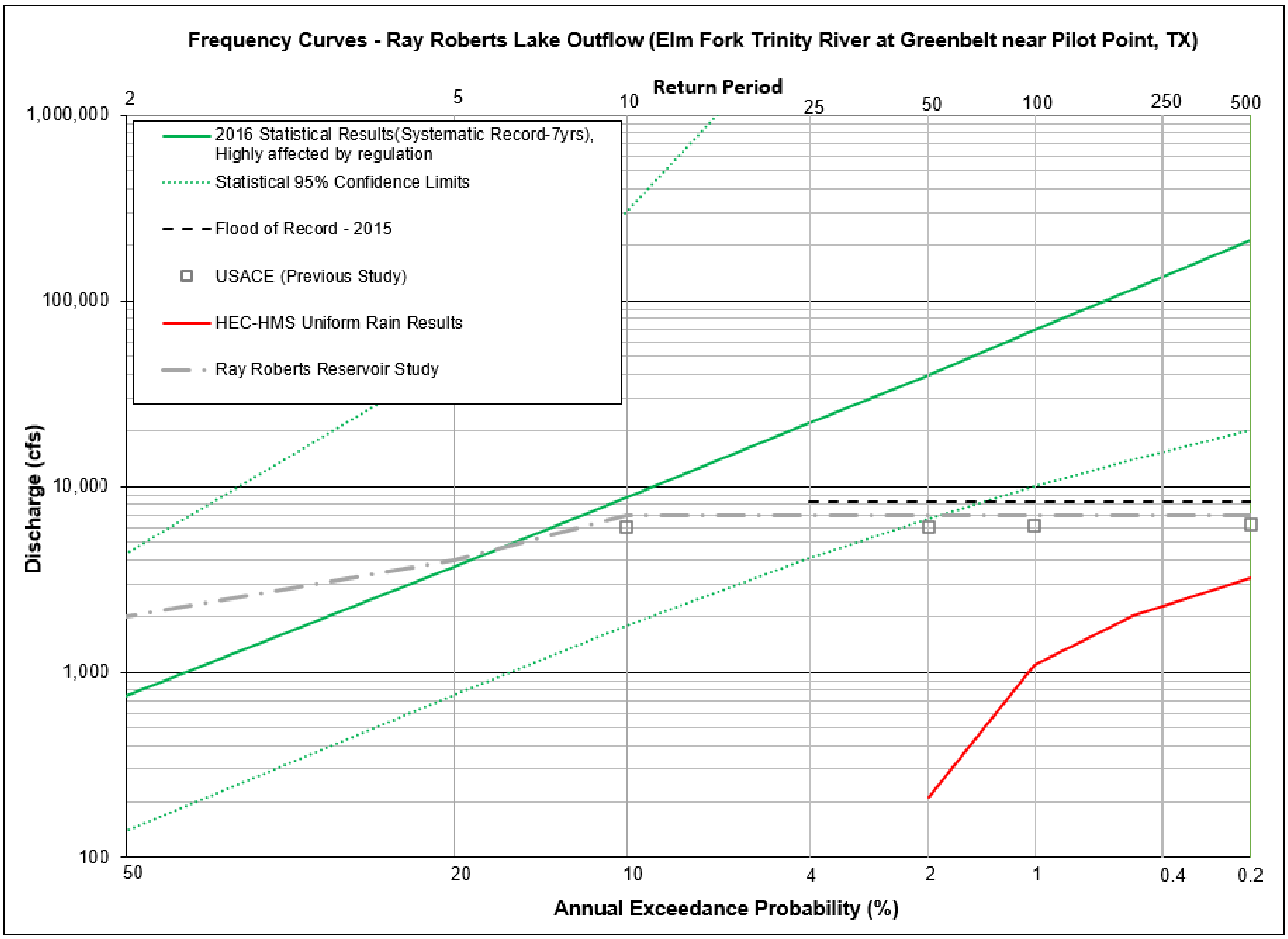


Figure 10.36: Flow Frequency Curve Comparison for Ray Roberts Lake Outflow

Table 10.29: Comparison of Frequency Flows at Clear Creek near Sanger Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	134,400		134,000	85,300		99,300		
0.004	200				62,300		78,900		
0.01	100	93,200		93,200	48,300		62,600		
0.02	50	68,500		68,500	36,700		45,700		
0.04	25			51,600	27,300		32,800		
0.1	10	30,400		30,400	17,400		19,000		
0.2	5				11,600		10,400		
0.5	2				5,500		6,000		

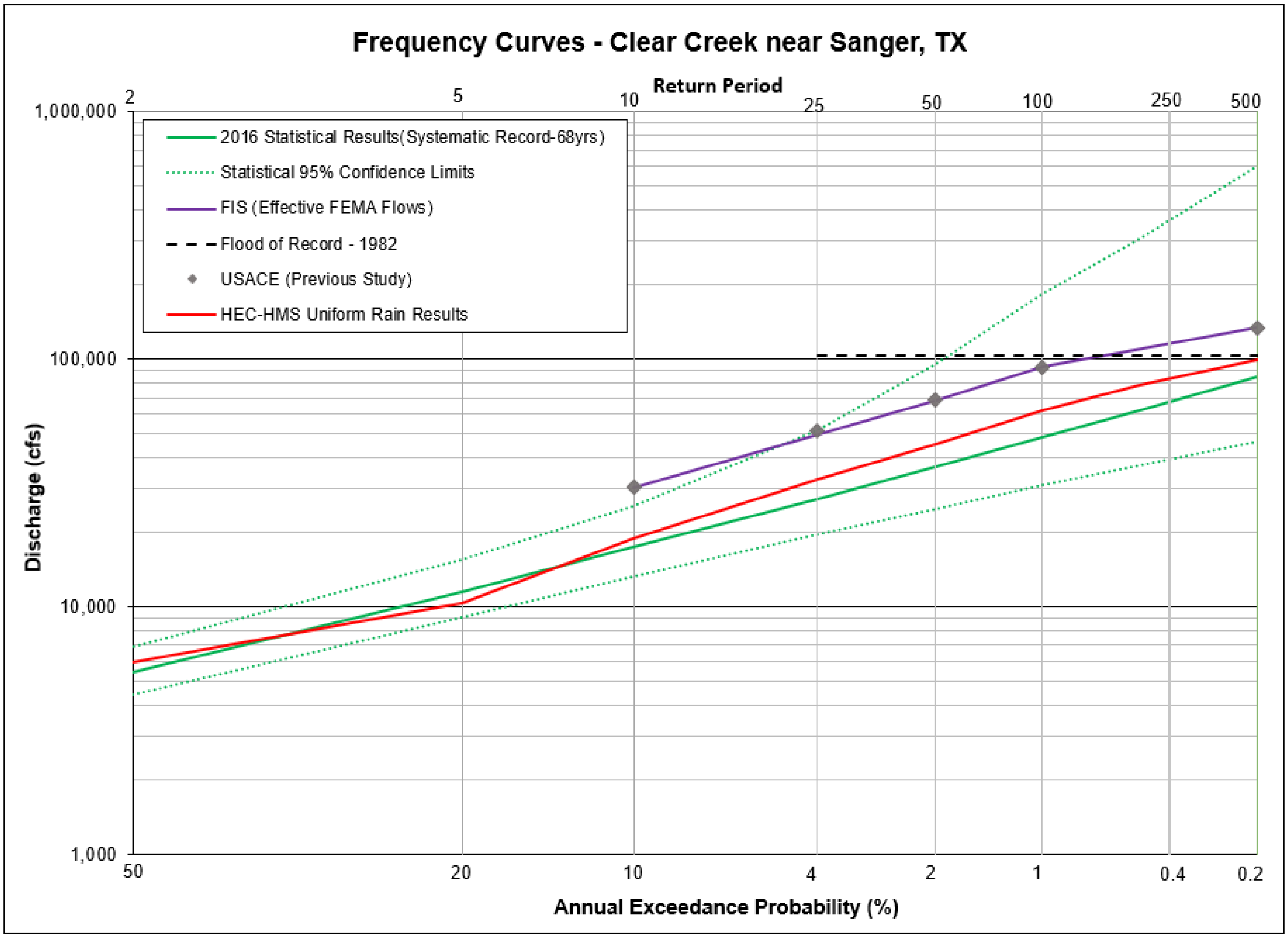


Figure 10.37: Flow Frequency Curve Comparison for Clear Creek near Sanger Gage

Figure 10.38 below provides a comparison between the 100-year calibrated rainfall-runoff model (HEC-HMS) results, observed annual peak flows, 100-year USGS regression equation results, and 100-year statistical hydrology results at the Clear Fork near Sanger USGS gage. The statistical hydrology results show how the 100-year statistical hydrology value has changed as each additional annual peak flow is added to the record. Generally, at least 300-400 years of record are needed before the 1% annual chance (100-yr) flow frequency estimates will stop significantly changing over time with additional years of record, unless additional information such as rainfall-runoff modeling estimates are utilized in the statistical analysis.

For this location, the HEC-HMS results are higher than the statistical hydrology estimate as the statistical hydrology result has changed over time, but are well within the statistical hydrology 95% confidence limits. The HEC-HMS results are also higher than the USGS regression equation value, which considers the drainage area below USACE reservoirs and other major reservoirs.

Because of these differences and the fact that there has been an event that has significantly exceeded the 100-yr HEC-HMS results, additional investigation was perfomed. Rainfall analysis was performed on the October 1981 event which resulted from the remains of Hurricane Norma. This event produced the largest observed peak flow at this gage. This peak flow (104,000 cfs) resulted from about 14 inches of rainfall over 48-hours. This rainfall amount is similar to the NOAA Atlas 14 500-yr rainfall amount of about 12.7 inches. Both the peak flow and rainfall amounts of the 1981 event are very similar to those from the 500-yr HEC-HMS model. While the 100-yr HEC-HMS results are higher than the statistical hydrology results and the regression equation results, the fact that the watershed has experienced a very large flood event that greatly exceeded the lower results from other methods, and that the 1981 event compares well with the 500-yr HEC-HMS results, the 100-yr result from the HEC-HMS model is considered a reasonable estimate of the 100-yr flood event.

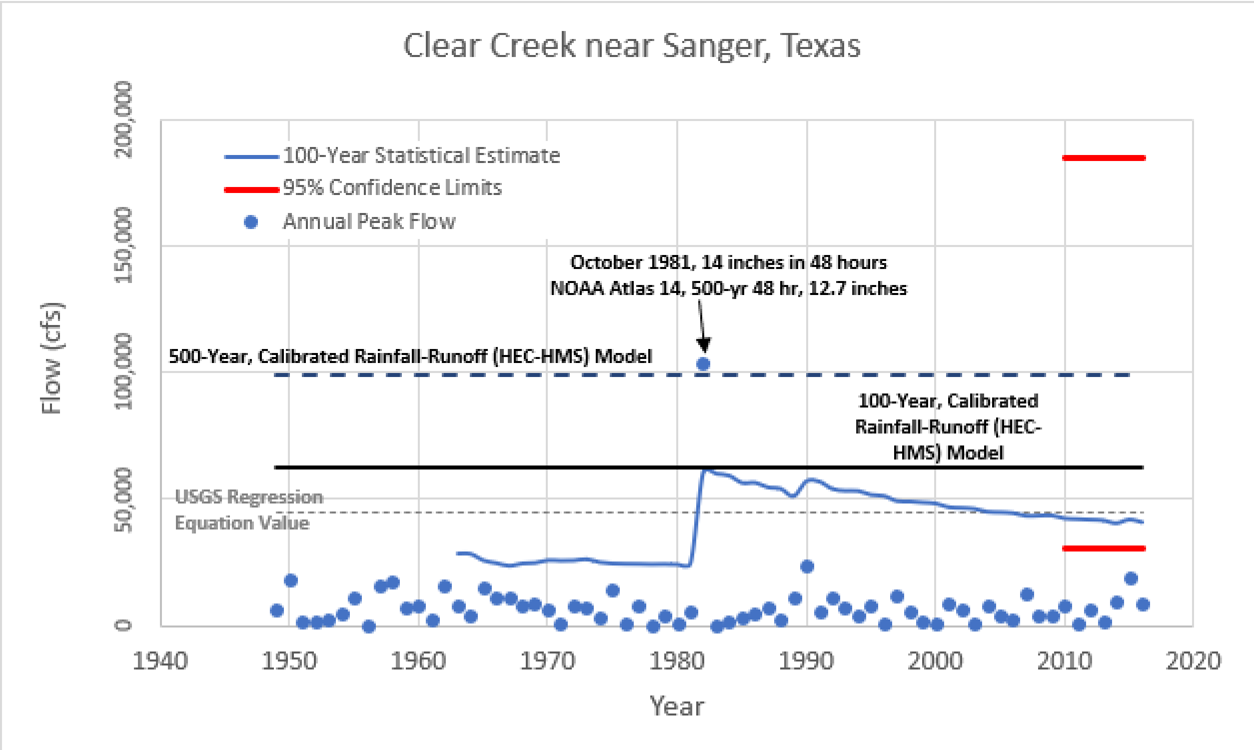


Figure 10.38 100-YR Flow Comparison for the Clear Creek near Sanger Gage

Table 10.30: Comparison of Frequency Flows at Little Elm Creek near Aubrey Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	40,700		40,700	49,100		35,700		
0.004	200				37,000		29,500		
0.01	100	24,100		24,100	29,200		24,700		
0.02	50	18,500		18,500	22,600		19,500		
0.04	25			13,900	16,900		15,200		
0.1	10	8,600		8,600	10,700		10,400		
0.2	5				7,000		7,400		
0.5	2				3,000		3,400		

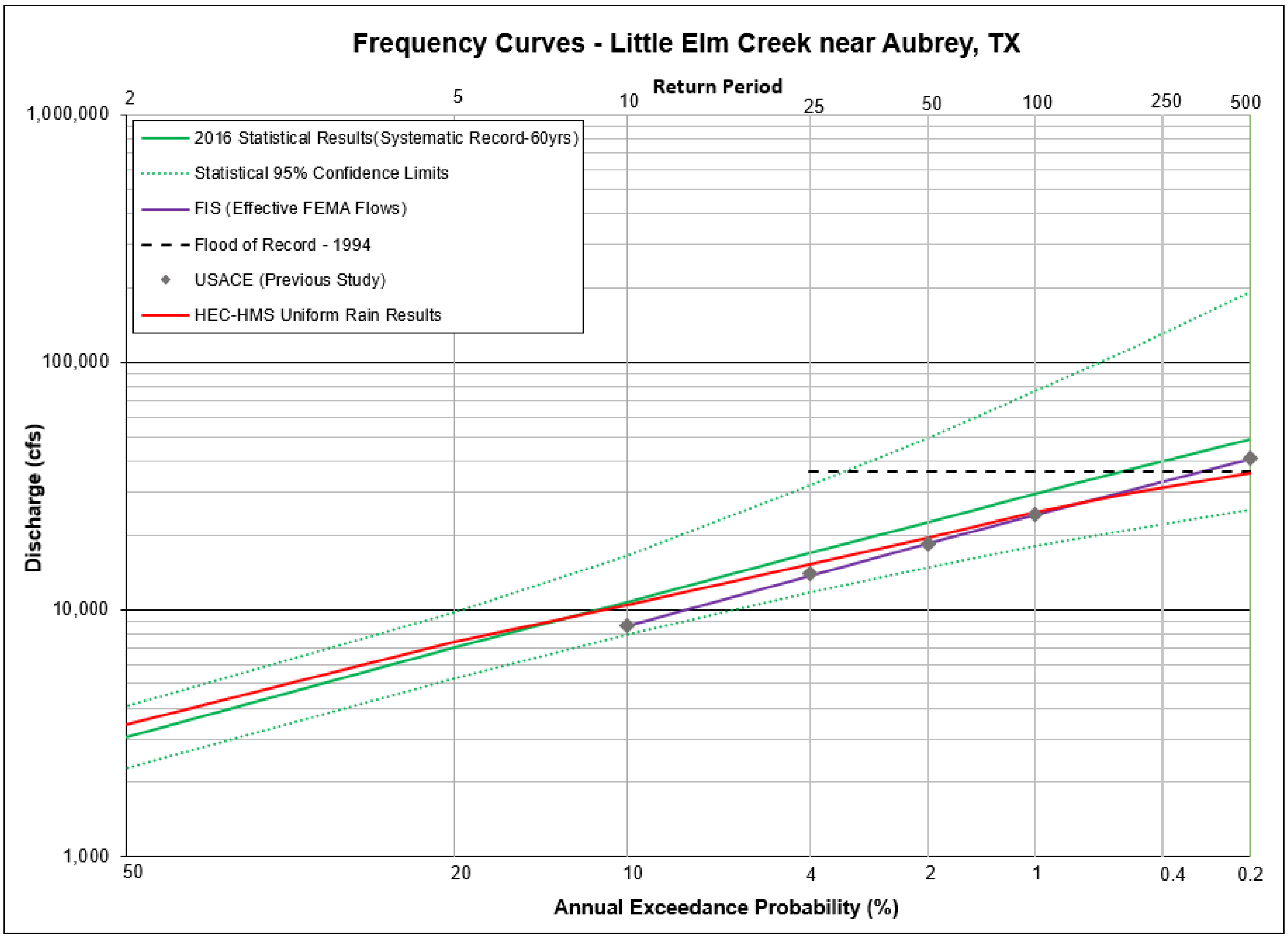


Figure 10.39: Flow Frequency Curve Comparison for Little Elm Creek near Aubrey Gage

Table 10.31: Comparison of Frequency Flows at Doe Branch at Hwy 380 near Prosper Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	38,000		38,000			23,800		
0.004	200						20,300		
0.01	100	28,700		28,700			17,700		
0.02	50	24,000		24,000			14,900		
0.04	25			19,500			12,500		
0.1	10	14,600		14,600			9,500		
0.2	5						7,200		
0.5	2						4,200		

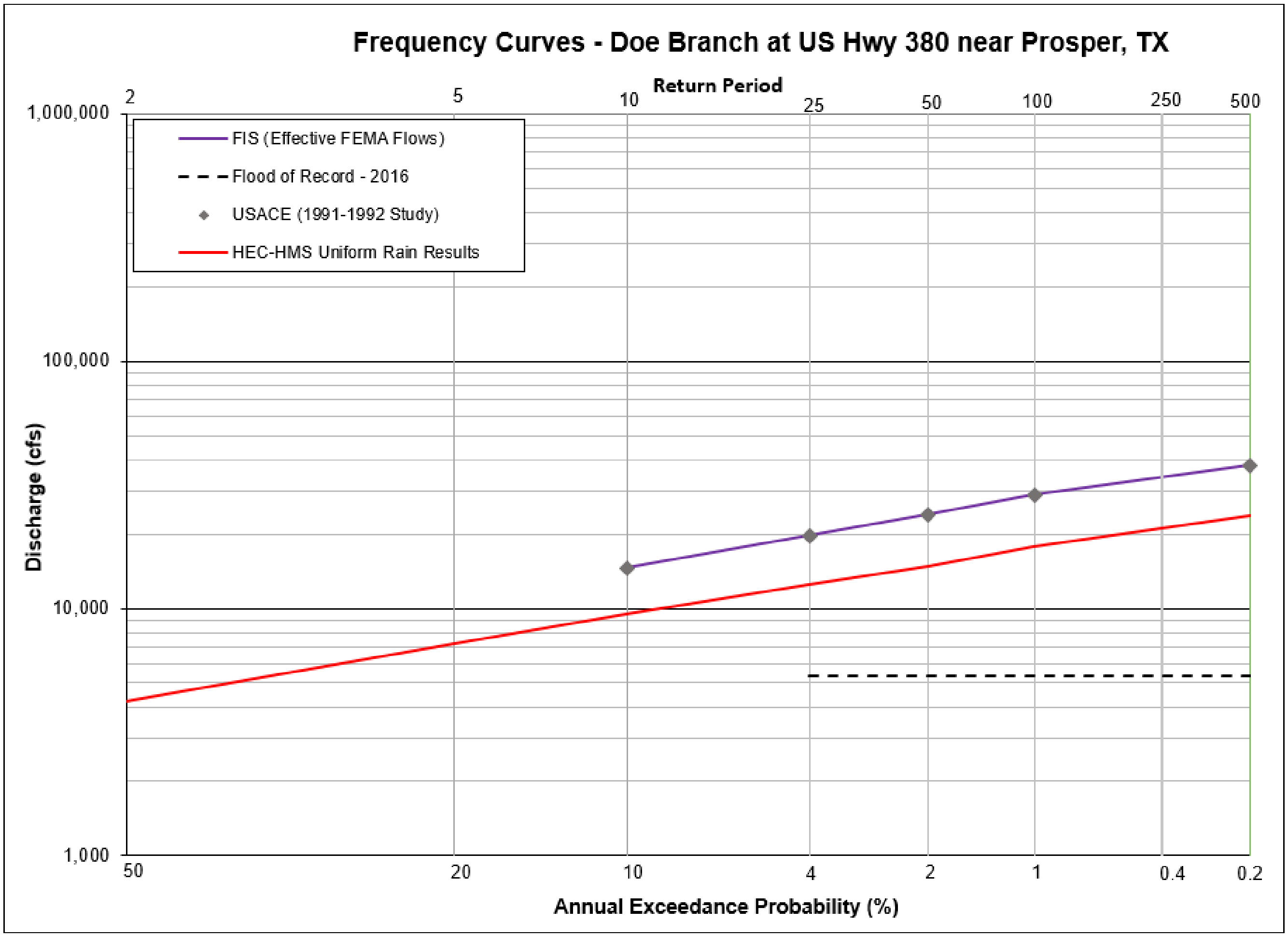


Figure 10.40: Flow Frequency Curve Comparison for Doe Branch at US Hwy 380 near Prosper Gage

Table 10.32: Comparison of Frequency Flows at Hickory Creek at Denton Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	68,000		68,000			55,800		
0.004	200						46,900		
0.01	100	47,300		47,300			40,300		
0.02	50	37,600		37,600			32,700		
0.04	25						26,400		
0.1	10	23,100		23,100			19,100		
0.2	5						13,600		
0.5	2						6,200		

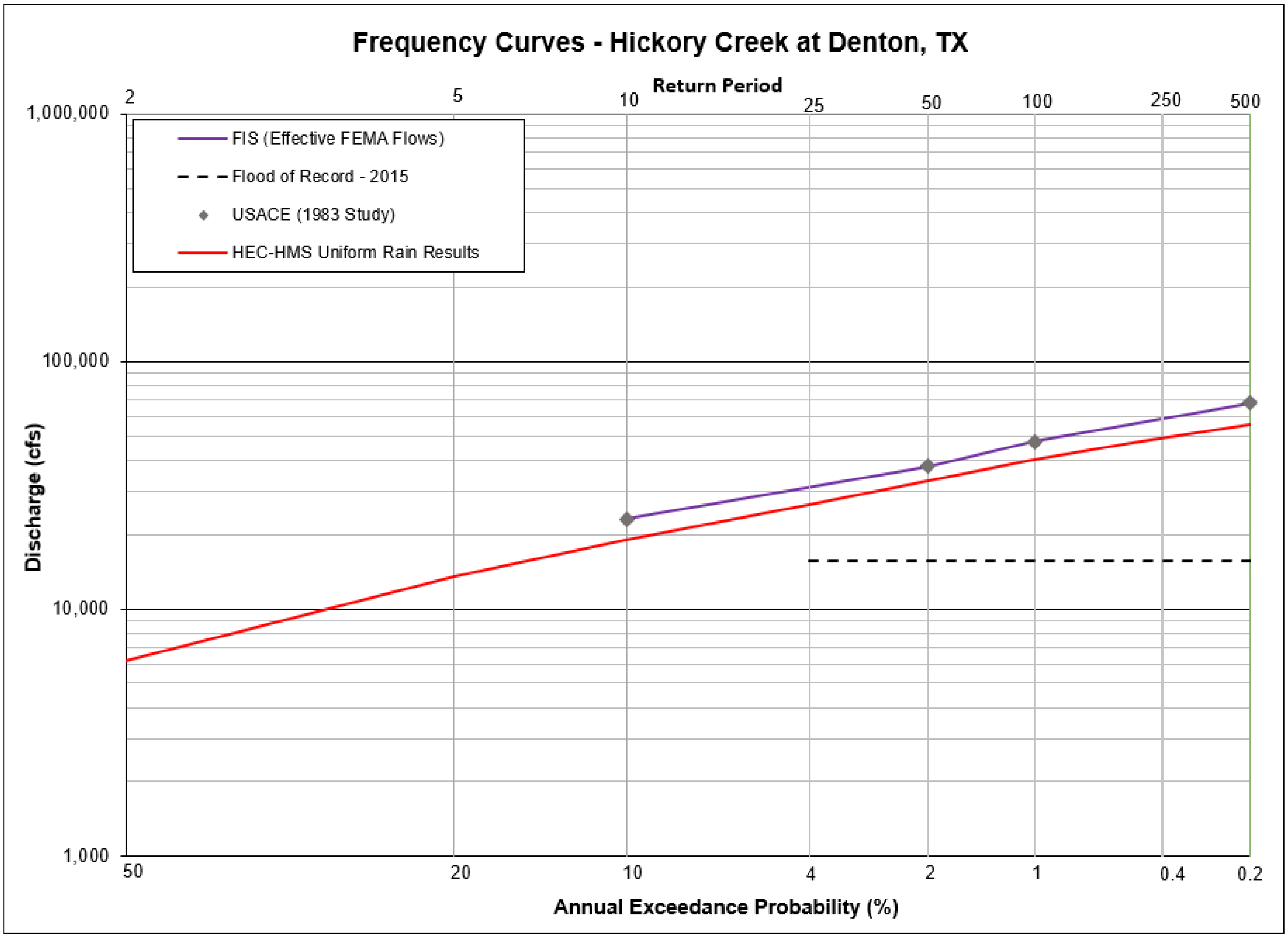


Figure 10.41: Flow Frequency Curve Comparison for Hickory Creek at Denton Gage

Table 10.33: Comparison of Frequency Flows for Lewisville Lake Outflow

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	57,000	57,000	57,000	35,200	23,600	17,400		50,000
0.004	200				27,600	19,600	10,100		36,000
0.01	100	21,000	21,000	21,000	22,500	16,700	5,500		26,500
0.02	50	7,000	10,200	10,200	18,100	14,000	1,500		17,900
0.04	25		7,000		14,200	10,800	0		9,400
0.1	10	1,700	7,000	7,000	9,700	8,500	0		7,000
0.2	5				6,800	6,300	0		7,000
0.5	2				3,500	3,500	0		4,000

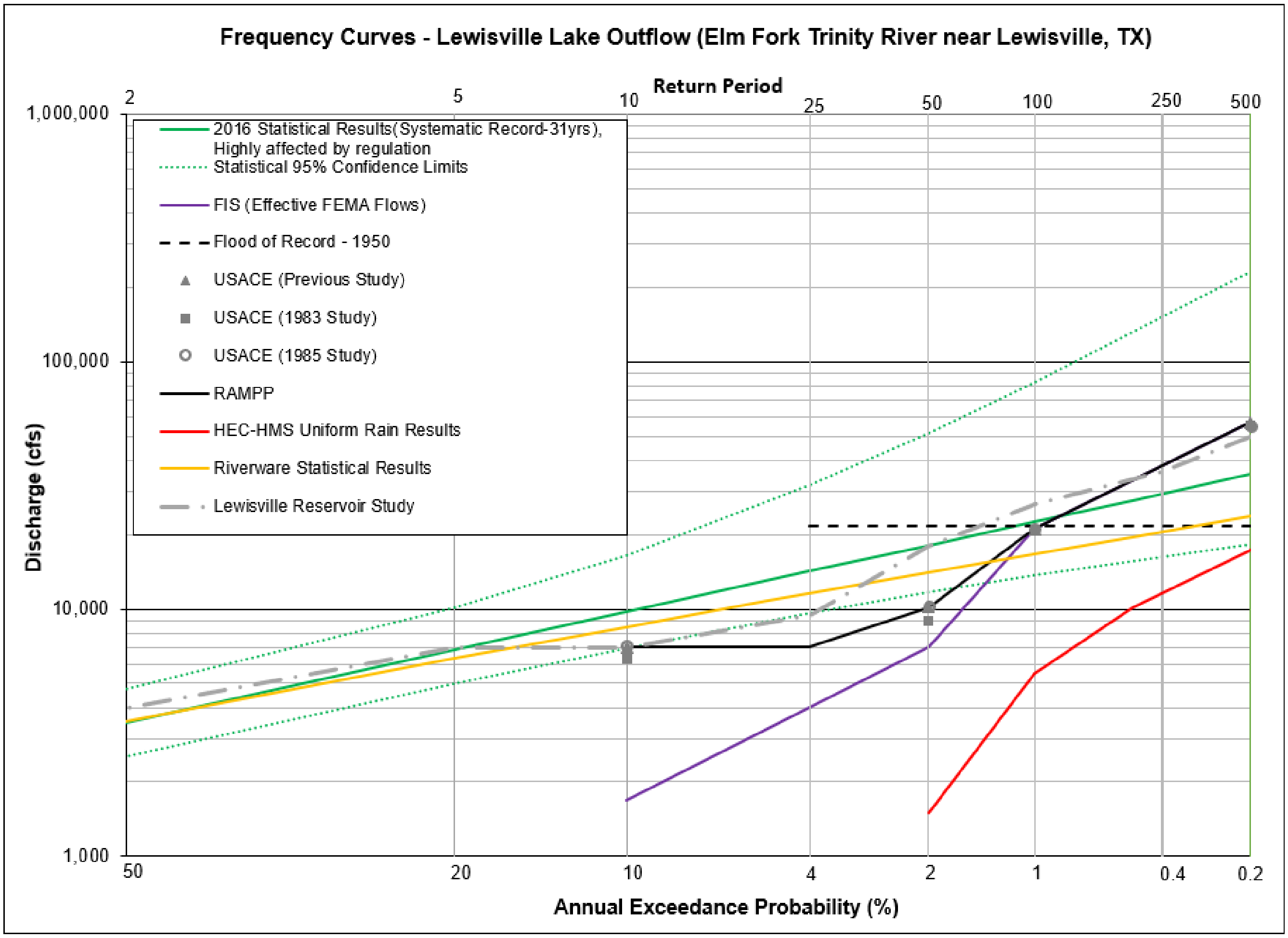


Figure 10.42: Flow Frequency Curve Comparison for Lewisville Lake Outflow

Table 10.34: Comparison of Frequency Flows at Indian Creek at FM2281 Carrolton Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	20,200		20,000					
0.004	200								
0.01	100	15,300		15,500					
0.02	50	13,400		13,700					
0.04	25								
0.1	10	8,800		9,700					
0.2	5								
0.5	2								

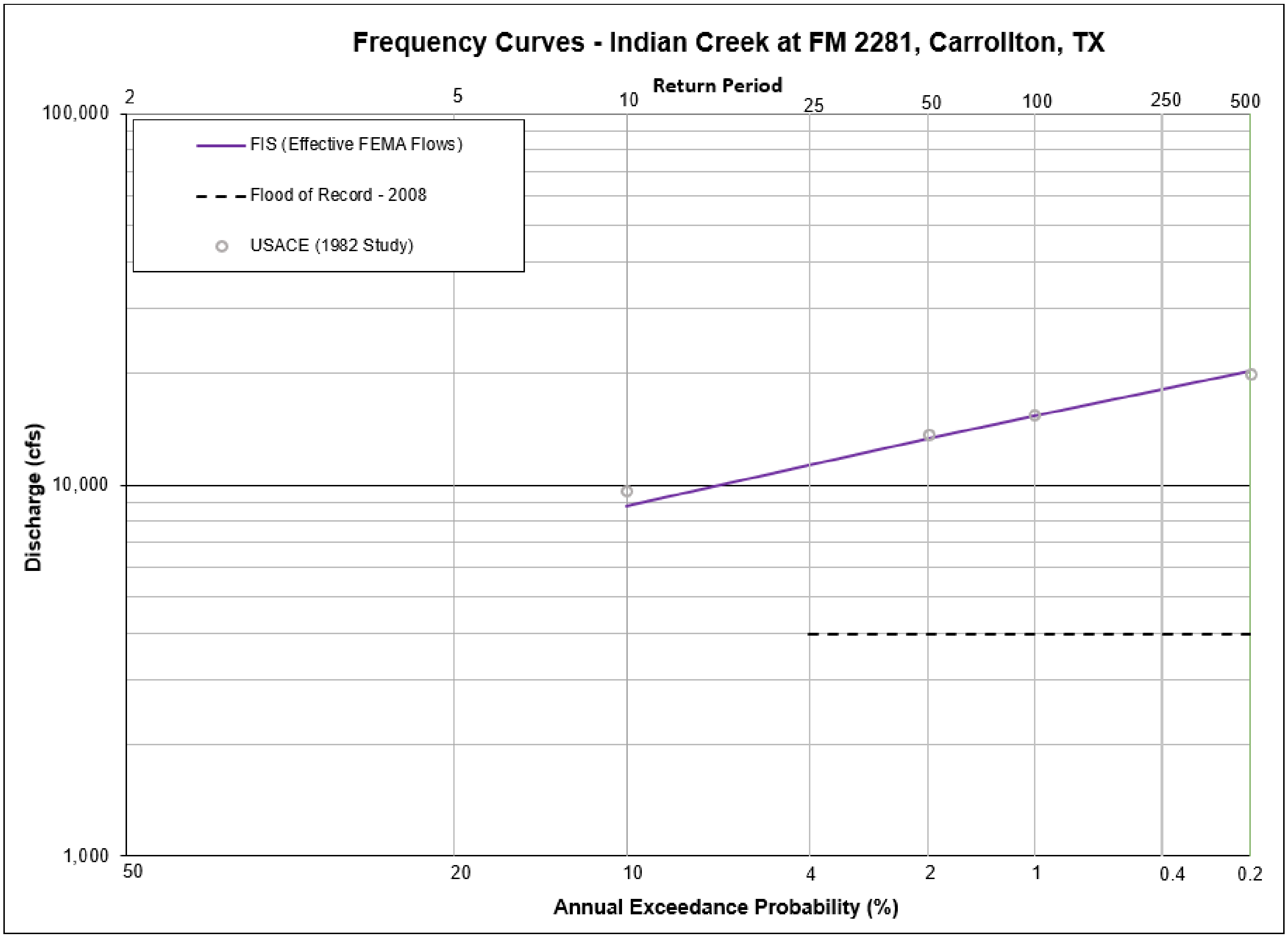


Figure 10.43: Flow Frequency Curve Comparison for Indian Creek at FM 2281 Carrolton Gage

Table 10.35: Comparison of Frequency Flows at Denton Creek near Justin Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	109,800		109,800	78,600		81,700	82,600	
0.004	200				59,900		62,900	62,700	
0.01	100	66,200		66,200	47,600		47,300	46,800	
0.02	50	48,000		48,000	36,800		35,900	35,700	
0.04	25			35,800	27,500		26,000	26,000	
0.1	10	20,200		20,200	17,300		16,000	17,400	
0.2	5				11,000		9,700	11,300	
0.5	2				4,400		4,100	4,500	

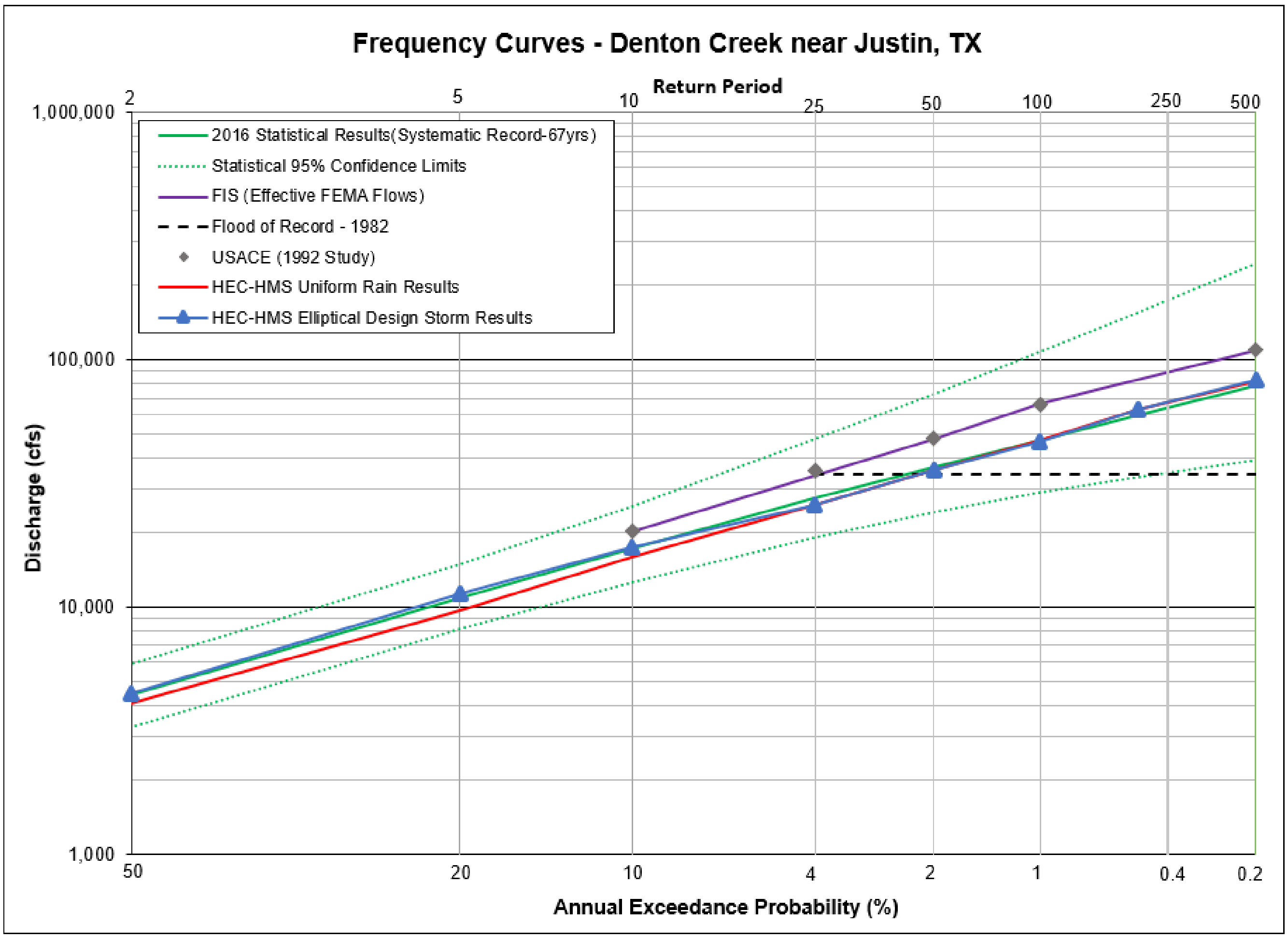


Figure 10.44: Flow Frequency Curve Comparison for Denton Creek near Justin Gage

Figure 10.45 below provides a comparison between the 100-year calibrated rainfall-runoff model (HEC-HMS) results, observed annual peak flows, 100-year USGS regression equation results, and 100-year statistical hydrology results at the Denton Creek near Justin USGS gage. The statistical hydrology results show how the 100-year statistical hydrology value has changed as each additional annual peak flow is added to the record. Generally, at least 300-400 years of record are needed before the 1% annual chance (100-yr) flow frequency estimates will stop significantly changing over time with additional years of record, unless additional information such as rainfall-runoff modeling estimates are utilized in the statistical analysis.

For this location, the HEC-HMS results have been both higher and lower than the statistical hydrology estimate as the statistical hydrology result has changed over time. The HEC-HMS results are well within the statistical hydrology 95% confidence limits and are similar to the statistical hydrology estimate using the full record length. The HEC-HMS results are also similar to the USGS regression equation value.

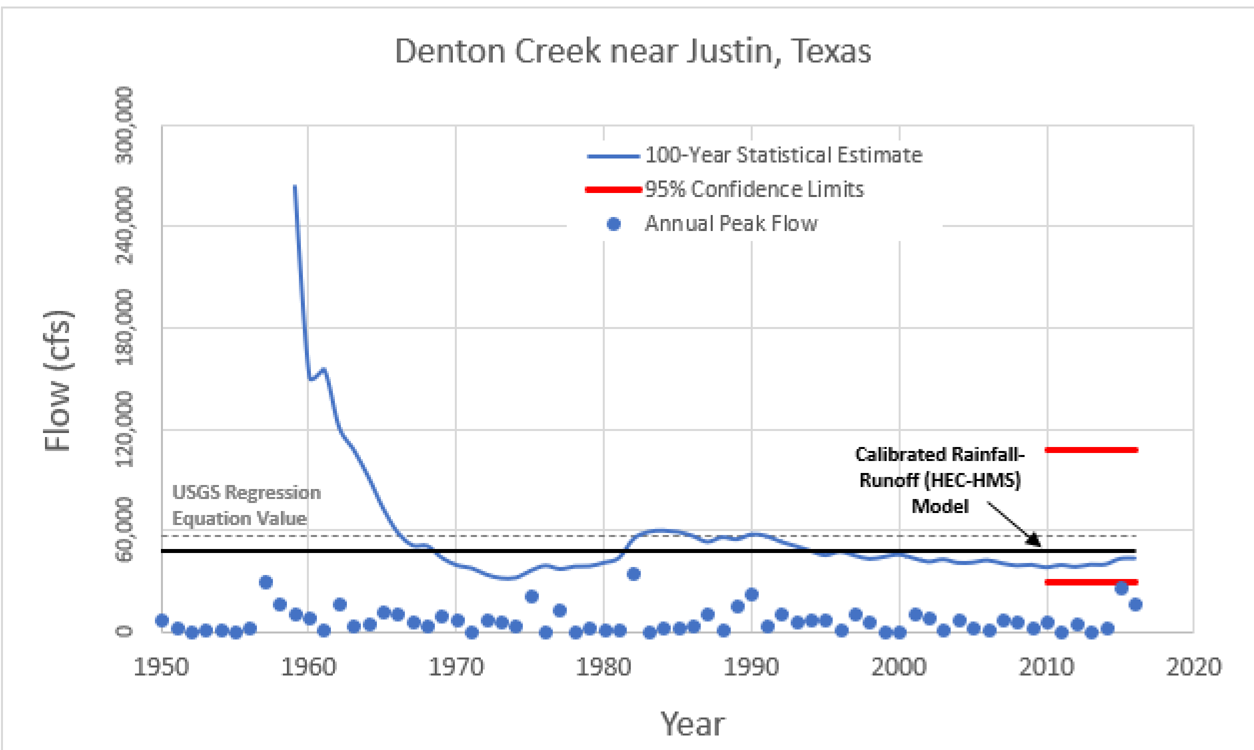


Figure 10.45 100-YR Flow Comparison for Denton Creek near Justin Gage

Table 10.36: Comparison of Frequency Flows for Grapevine Lake Outflow

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	36,200		19,700	18,900		19,500		30,800
0.004	200				13,900		9,500		20,100
0.01	100	15,600		15,600	10,800		3,900		13,100
0.02	50	13,800		13,800	8,300		0		7,700
0.04	25				6,300		0		3,100
0.1	10	10,000		10,000	4,200		0		2,000
0.2	5				2,900		0		2,000
0.5	2				1,600		0		2,000

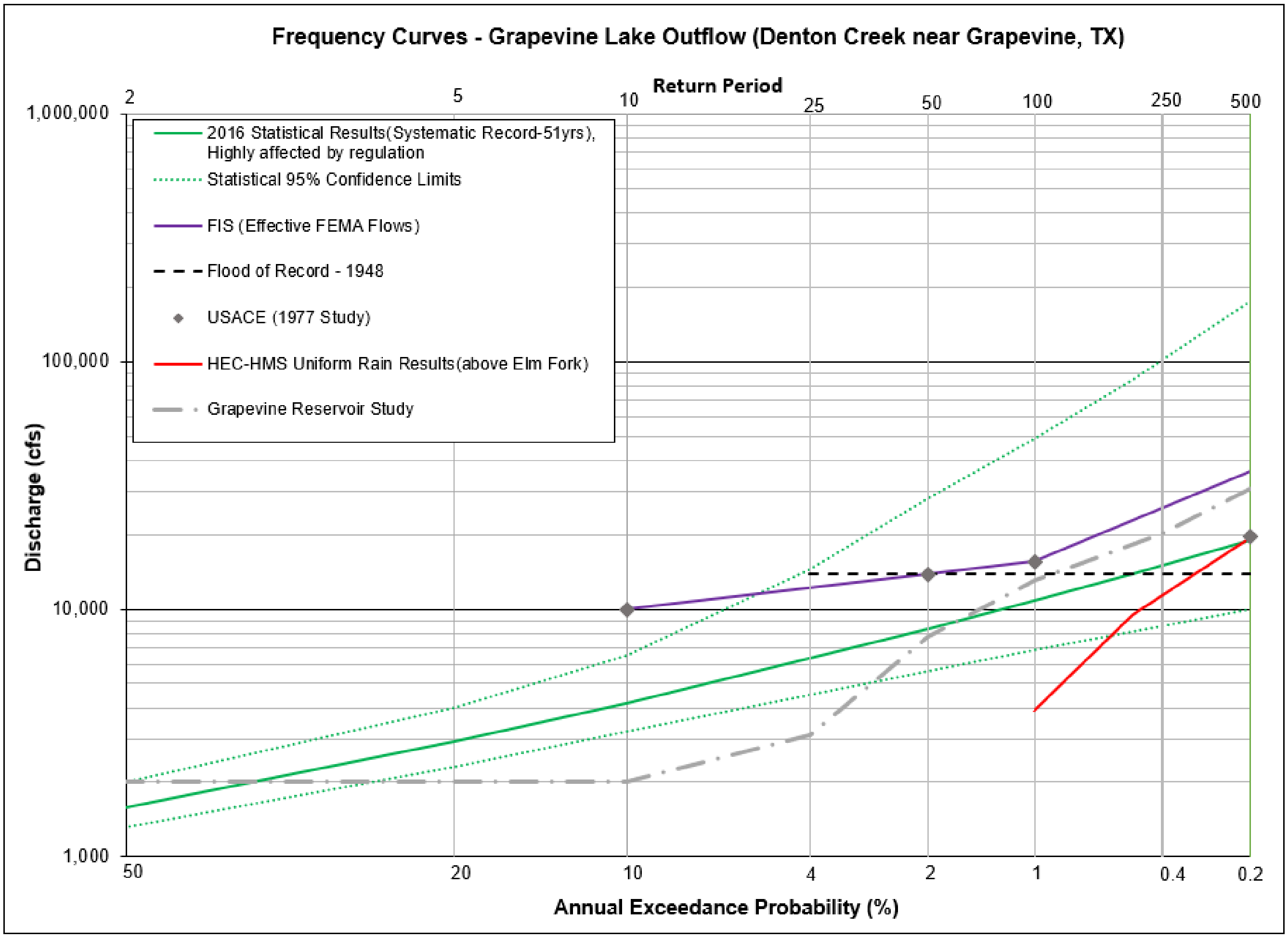


Figure 10.46: Flow Frequency Curve Comparison for Grapevine Lake Outflow

Table 10.37: Comparison of Frequency Flows at Elm Fork Trinity River near Carrolton Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	70,700	65,400	70,700	53,100	51,900	51,200	49,300	
0.004	200				40,400	37,400	43,200	41,500	
0.01	100	43,500	43,600	43,500	32,500	29,000	37,200	35,600	
0.02	50	33,200	34,800	33,200	25,900	22,400	31,500	30,100	
0.04	25		28,500		20,300	15,700	26,700	25,600	
0.1	10	17,900	21,600	17,900	14,200	11,800	17,100	17,700	
0.2	5				10,500	8,700	11,700	13,400	
0.5	2				6,200	5,400	6,700	7,500	

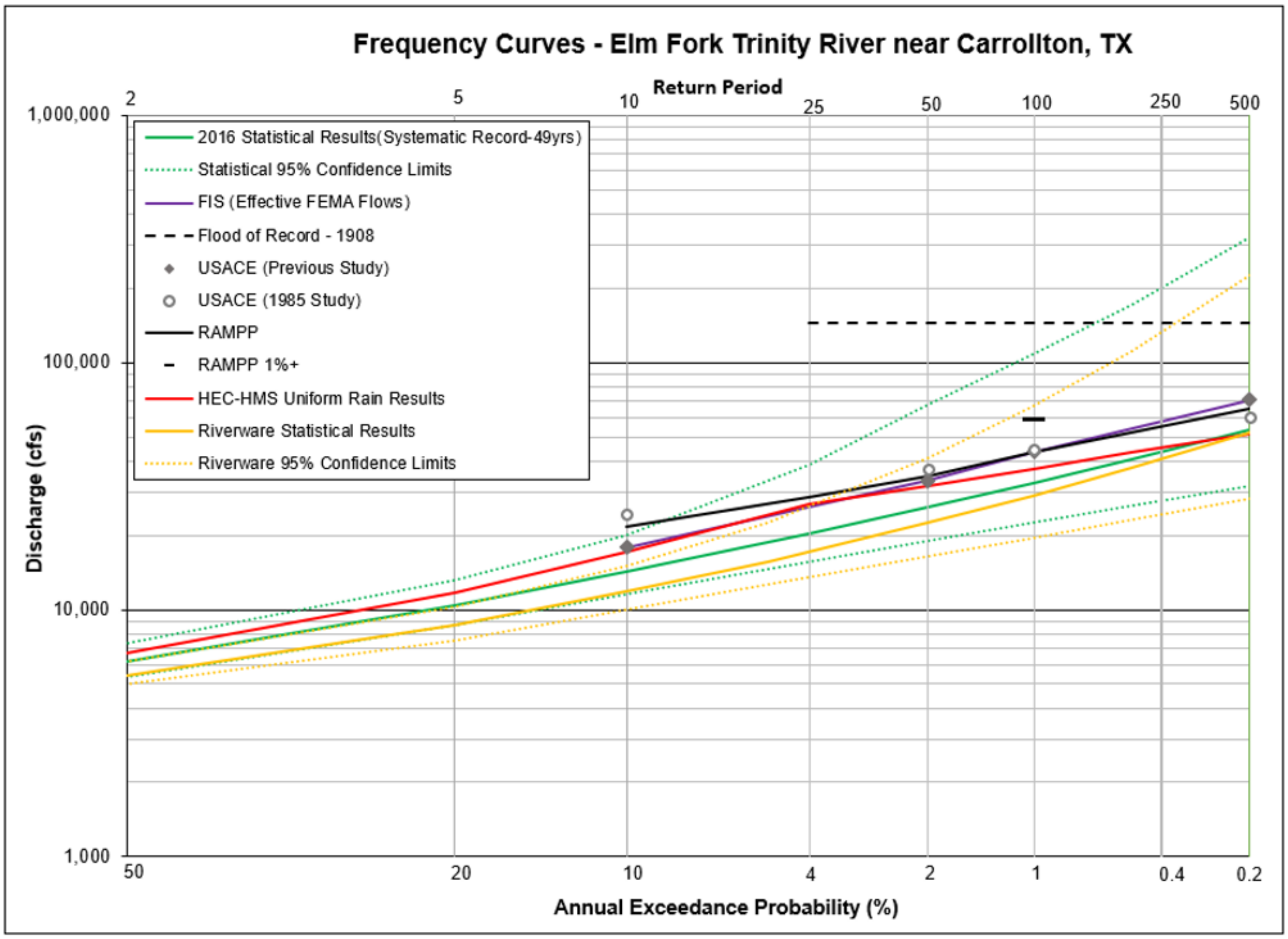


Figure 10.47: Flow Frequency Curve Comparison for Elm Fork Trinity River near Carrolton Gage

Figure 10.48 below provides a comparison between the 100-year calibrated rainfall-runoff model (HEC-HMS) results, observed annual peak flows, 100-year USGS regression equation results, and 100-year statistical hydrology results at the Elm Fork Trinity River near Carrolton USGS gage. The statistical hydrology results show how the 100-year statistical hydrology value has changed as each additional annual peak flow is added to the record. Generally, at least 300-400 years of record are needed before the 1% annual chance (100-yr) flow frequency estimates will stop significantly changing over time with additional years of record, unless additional information such as rainfall-runoff modeling estimates are utilized in the statistical analysis.

For this location, the HEC-HMS results have been both higher and lower than the statistical hydrology estimate as the statistical hydrology result has changed over time. The HEC-HMS results are well within the statistical hydrology 95% confidence limits and are similar to the statistical hydrology estimate using the full record length. The HEC-HMS results are higher than the USGS regression equation value, which considers the drainage area below USACE reservoirs and other major reservoirs and has been nearly equaled or exceeded several times.

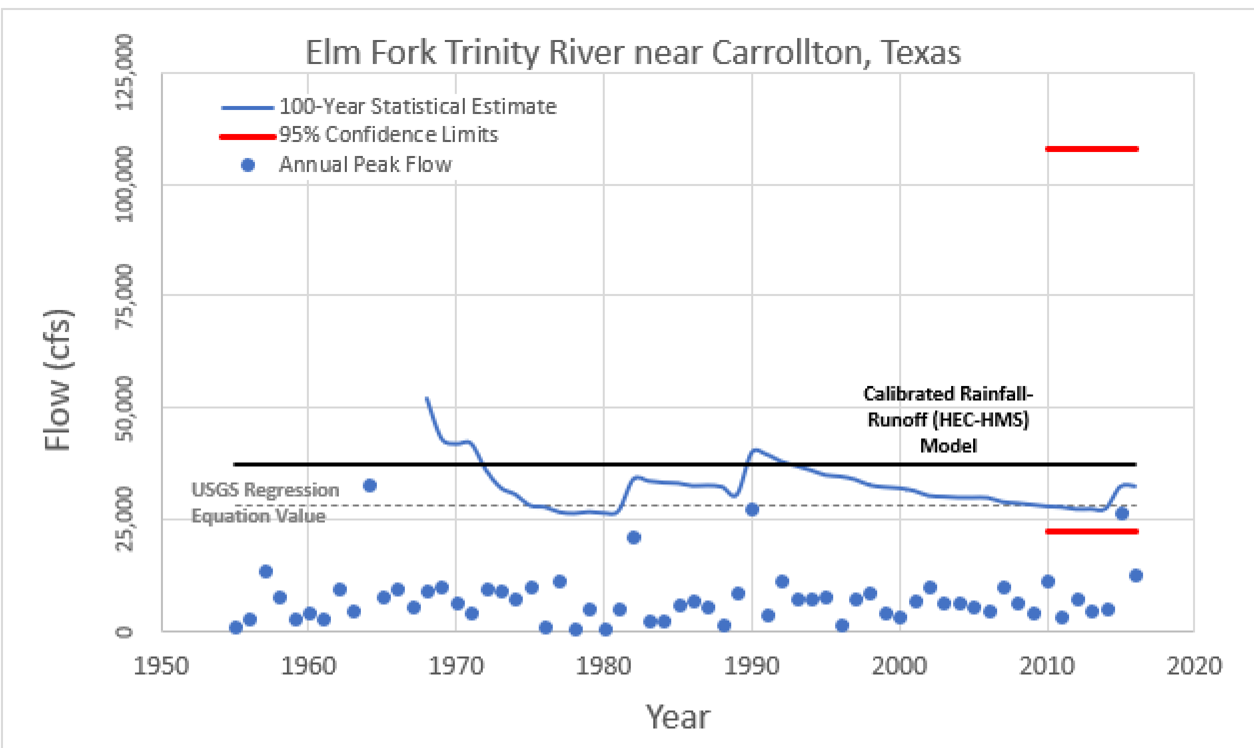


Figure 10.48 100-YR Flow Comparison for the Elm Fork Trinity River near Carrolton Gage

Table 10.38: Comparison of Frequency Flows at Elm Fork Trinity River at Spur 348 in Irvning Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	67,300	61,400	67,300			62,400	59,100	
0.004	200						52,800	49,400	
0.01	100	39,400	42,900	39,400			45,100	42,400	
0.02	50	29,800	34,900	29,800			37,100	35,000	
0.04	25		28,100				30,300	28,800	
0.1	10	20,200	20,400	20,200			19,100	20,000	
0.2	5						15,000	15,400	
0.5	2						10,000	10,800	

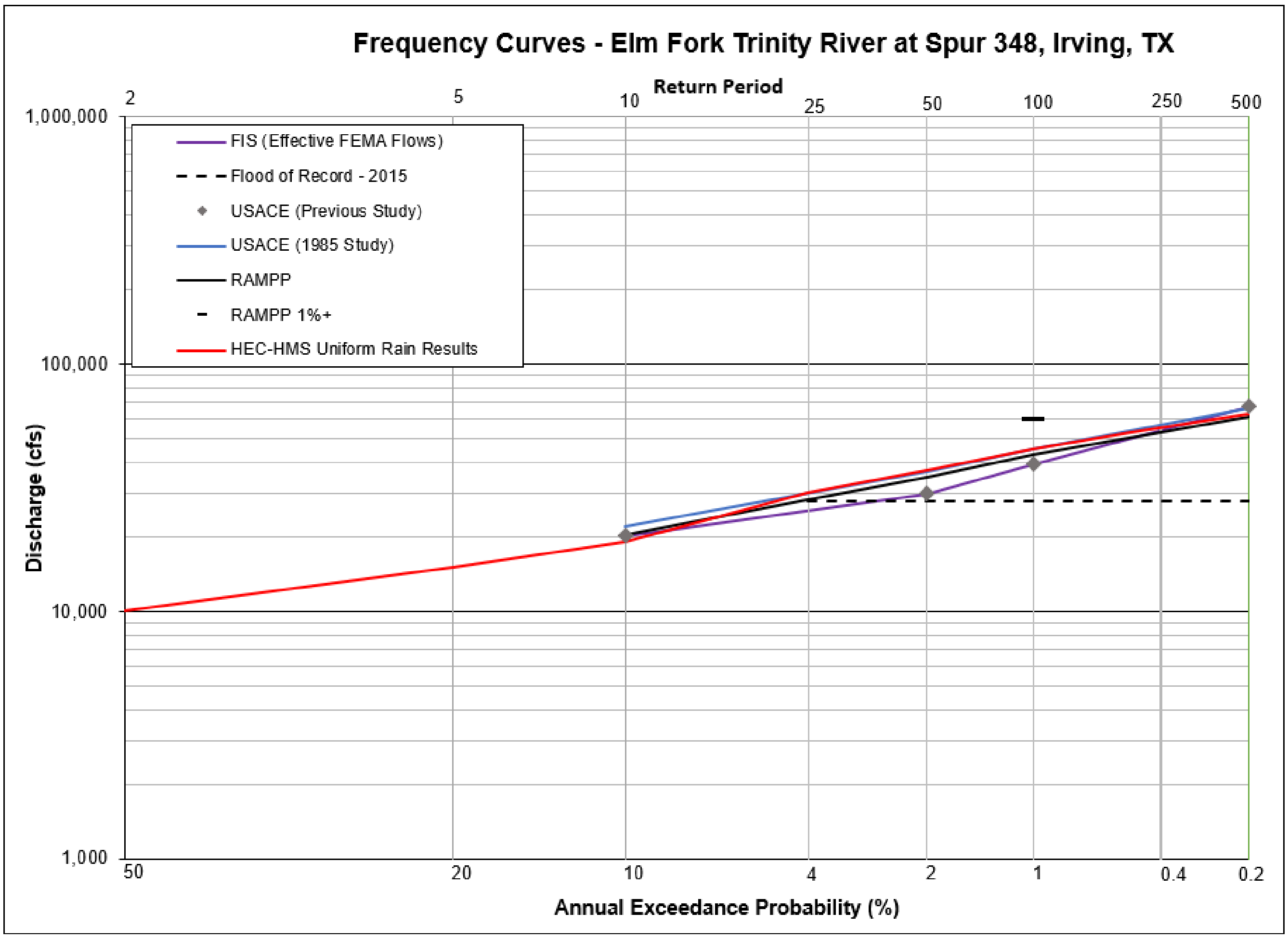


Figure 10.49: Flow Frequency Curve Comparison for Elm Fork Trinity River at Spur 348 Gage

Table 10.39: Comparison of Frequency Flows at Elm Fork Trinity River below Bachman Branch (at Frasier Dam) Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	50,000	59,700	50,000			57,700	55,900	
0.004	200						48,500	46,900	
0.01	100	37,500	41,400	37,500			41,700	40,400	
0.02	50	28,100	32,600	28,100			33,700	32,700	
0.04	25		25,500				27,100	26,600	
0.1	10	16,800	18,800	16,800			17,900	19,100	
0.2	5						14,100	15,000	
0.5	2						9,100	10,700	

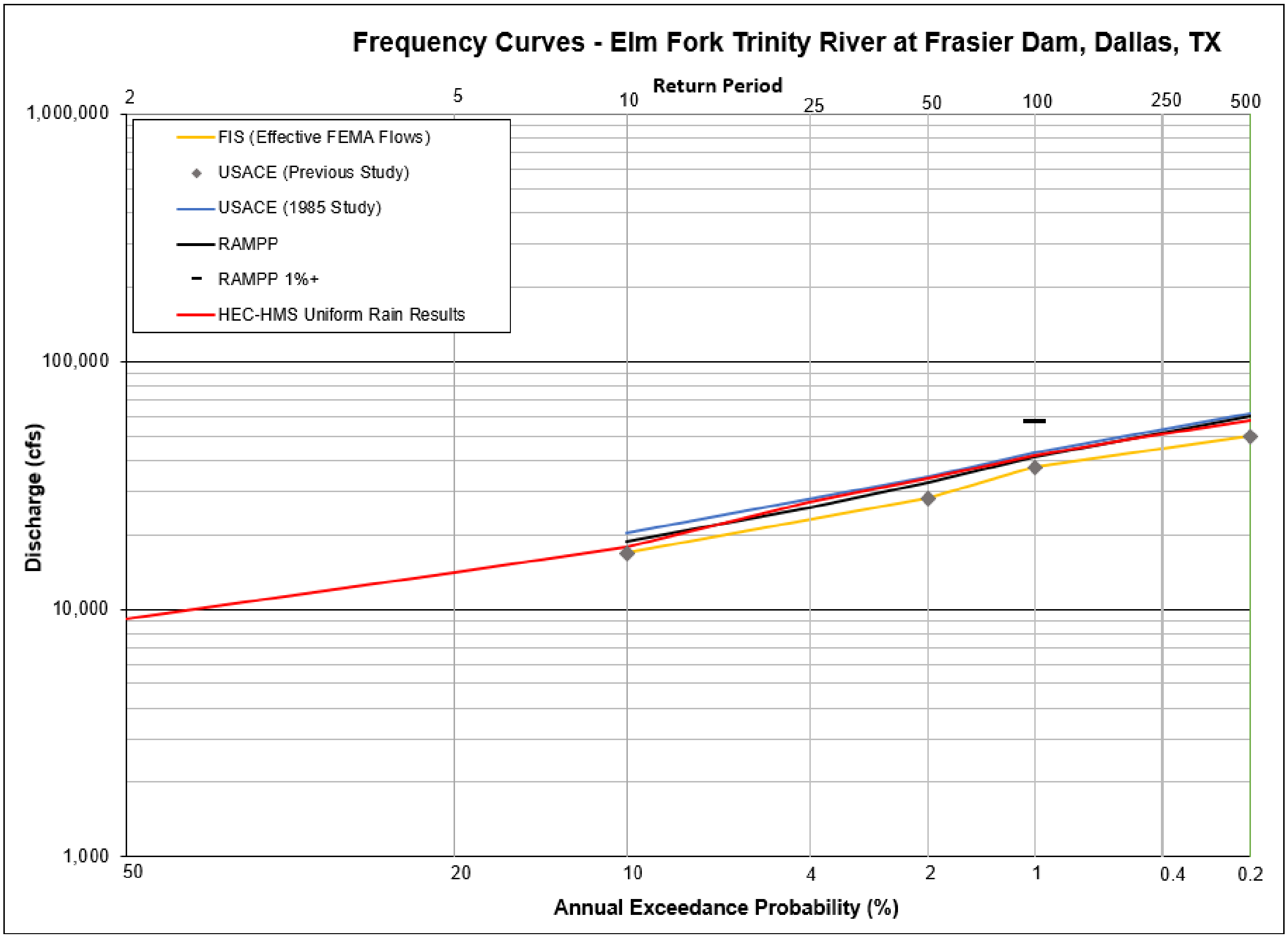


Figure 10.50: Flow Frequency Curve Comparison for Elm Fork Trinity River at Frasier Dam Gage

Table 10.40: Comparison of Frequency Flows at Turtle Creek at Dallas Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	17,600		20,900	11,900				
0.004	200				10,500				
0.01	100	13,000		16,600	9,500				
0.02	50	11,500		14,800	8,400				
0.04	25				7,300				
0.1	10	7,800		10,800	5,900				
0.2	5				4,800				
0.5	2				3,100				

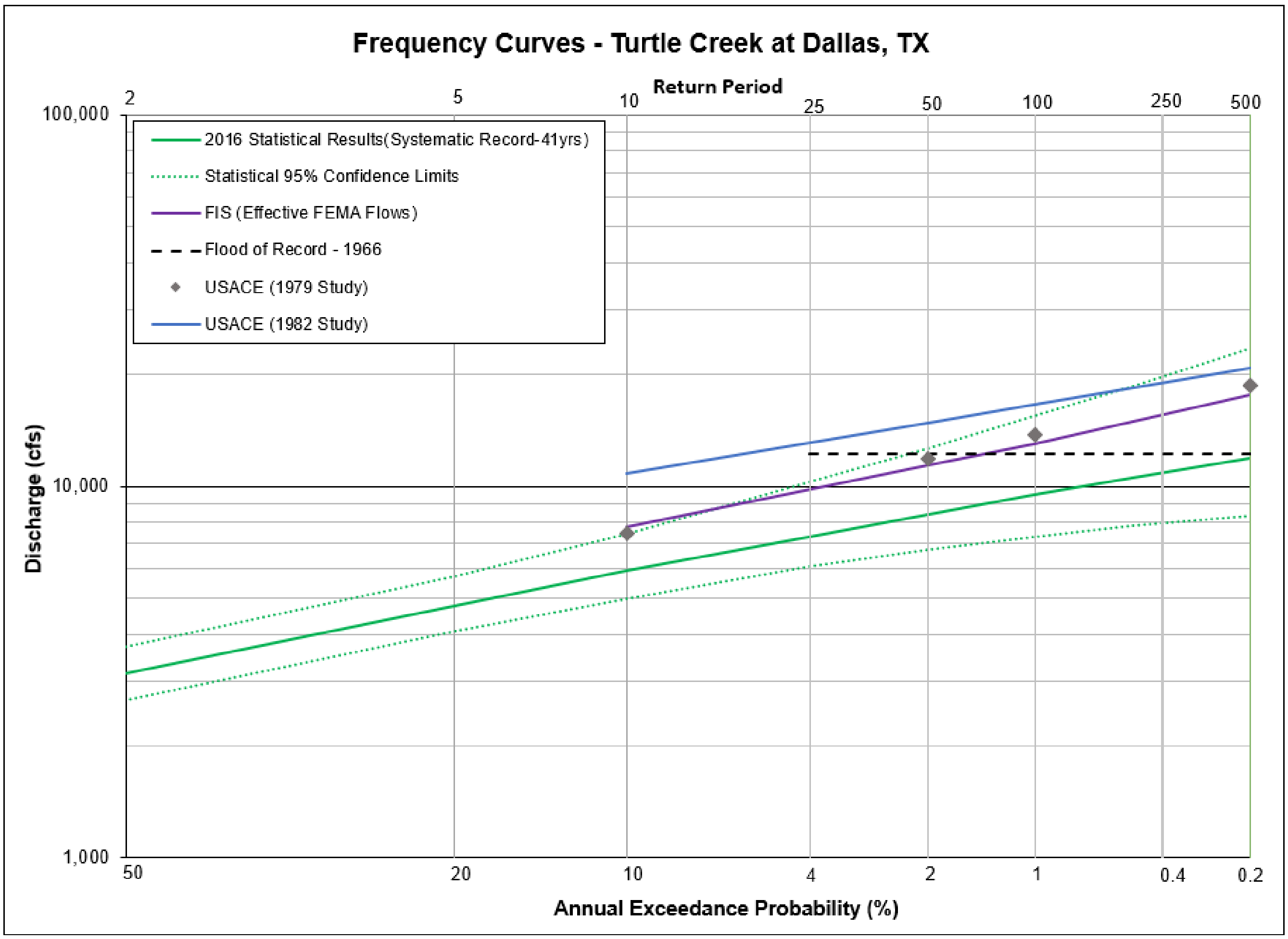


Figure 10.51: Flow Frequency Curve Comparison for Turtle Creek at Dallas Gage

Table 10.41: Comparison of Frequency Flows at Trinity River at Dallas Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	202,700	191,800		120,200	115,300	209,500	181,500	
0.004	200				101,400	95,900	162,400	138,900	
0.01	100	115,800	119,900		88,100	82,200	128,500	113,100	
0.02	50	95,100	97,000		75,400	69,200	100,200	88,500	
0.04	25		73,400		63,400	53,100	76,800	66,200	
0.1	10	51,500	45,100		48,400	41,700	42,800	42,100	
0.2	5				37,400	30,900	31,600	31,000	
0.5	2				22,800	17,000	18,800	19,000	

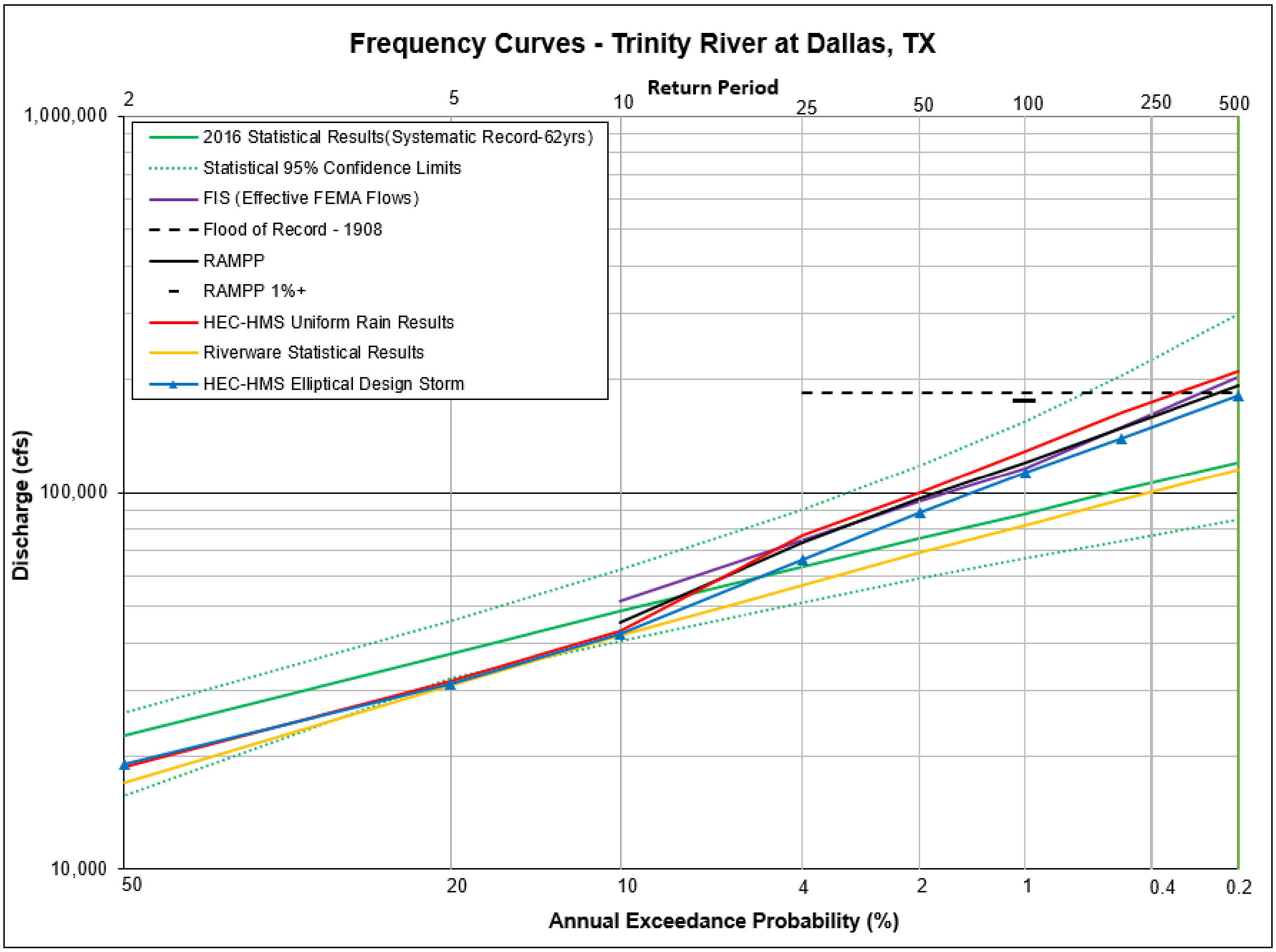


Figure 10.52: Flow Frequency Curve Comparison for Trinity River at Dallas Gage

Figure 10.53 below provides a comparison between the 100-year calibrated rainfall-runoff model (HEC-HMS) results, observed annual peak flows, 100-year USGS regression equation results, and 100-year statistical hydrology results at the Trinity River at Dallas USGS gage. The statistical hydrology results show how the 100-year statistical hydrology value has changed as each additional annual peak flow is added to the record. Generally, at least 300-400 years of record are needed before the 1% annual chance (100-yr) flow frequency estimates will stop significantly changing over time with additional years of record, unless additional information such as rainfall-runoff modeling estimates are utilized in the statistical analysis.

For this location, the HEC-HMS results have been both higher and lower than the statistical hydrology estimate as the statistical hydrology result has changed over time. The HEC-HMS results are well within the statistical hydrology 95% confidence limits and are higher than the statistical hydrology estimate using the full record length. The HEC-HMS results are slightly higher than the USGS regression equation value, which considers the drainage area below USACE reservoirs and other major reservoirs.

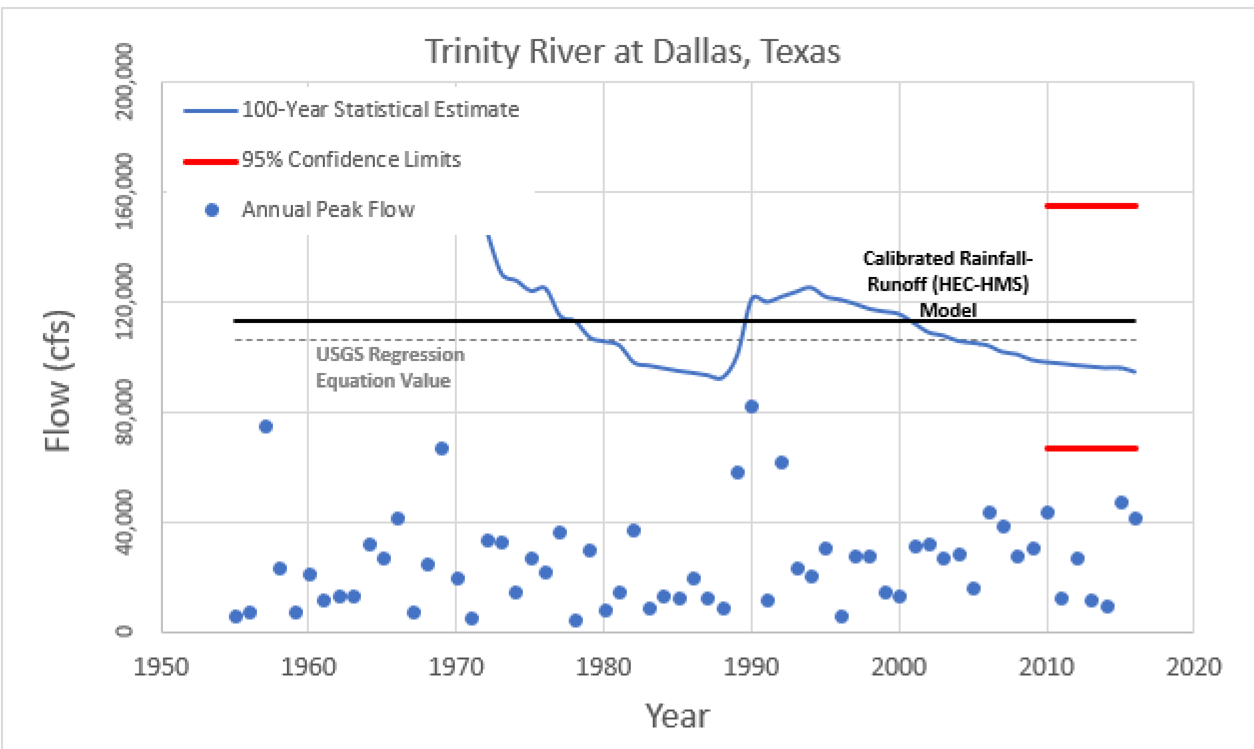


Figure 10.53 100-YR Flow Comparison for Trinity River at Dallas Gage

Table 10.42: Comparison of Frequency Flows at White Rock Creek at Greenville Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	64,300		55,200	55,500		68,700		
0.004	200				50,700		59,600		
0.01	100	55,400		41,400	46,800		52,900		
0.02	50	49,300		36,000	42,500		45,900		
0.04	25				38,000		39,500		
0.1	10	32,900		24,200	31,200		30,800		
0.2	5				25,500		24,400		
0.5	2				16,200		16,300		

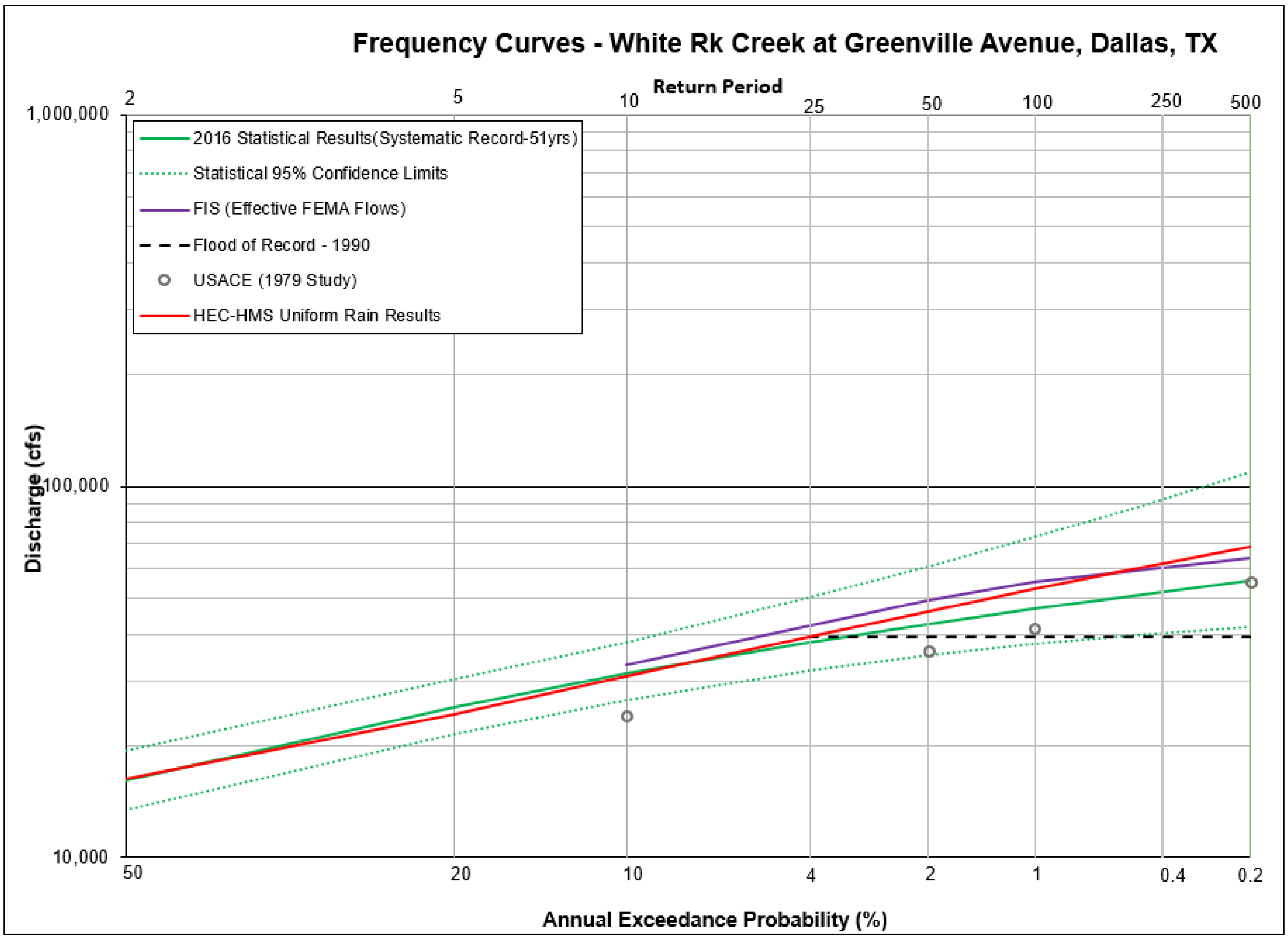


Figure 10.54: Flow Frequency Curve Comparison for White Rock Creek at Greenville Ave, Dallas Gage

Figure 10.55 below provides a comparison between the 100-year calibrated rainfall-runoff model (HEC-HMS) results, observed annual peak flows, 100-year USGS regression equation results, and 100-year statistical hydrology results at the White Rock Creek at Greenville Ave, Dallas USGS gage. The statistical hydrology results show how the 100-year statistical hydrology value has changed as each additional annual peak flow is added to the record. Generally, at least 300-400 years of record are needed before the 1% annual chance (100-yr) flow frequency estimates will stop significantly changing over time with additional years of record, unless additional information such as rainfall-runoff modeling estimates are utilized in the statistical analysis.

For this location, the HEC-HMS results have been both higher and lower than the statistical hydrology estimate as the statistical hydrology result has changed over time. The HEC-HMS results are well within the statistical hydrology 95% confidence limits and are similar to the statistical hydrology estimate using the full record length. The HEC-HMS results are much higher than the USGS regression equation value, which considers the drainage area below USACE reservoirs and other major reservoirs, and has been exceeded several times, likely due to the neary fully urbanized condition of the watershed.

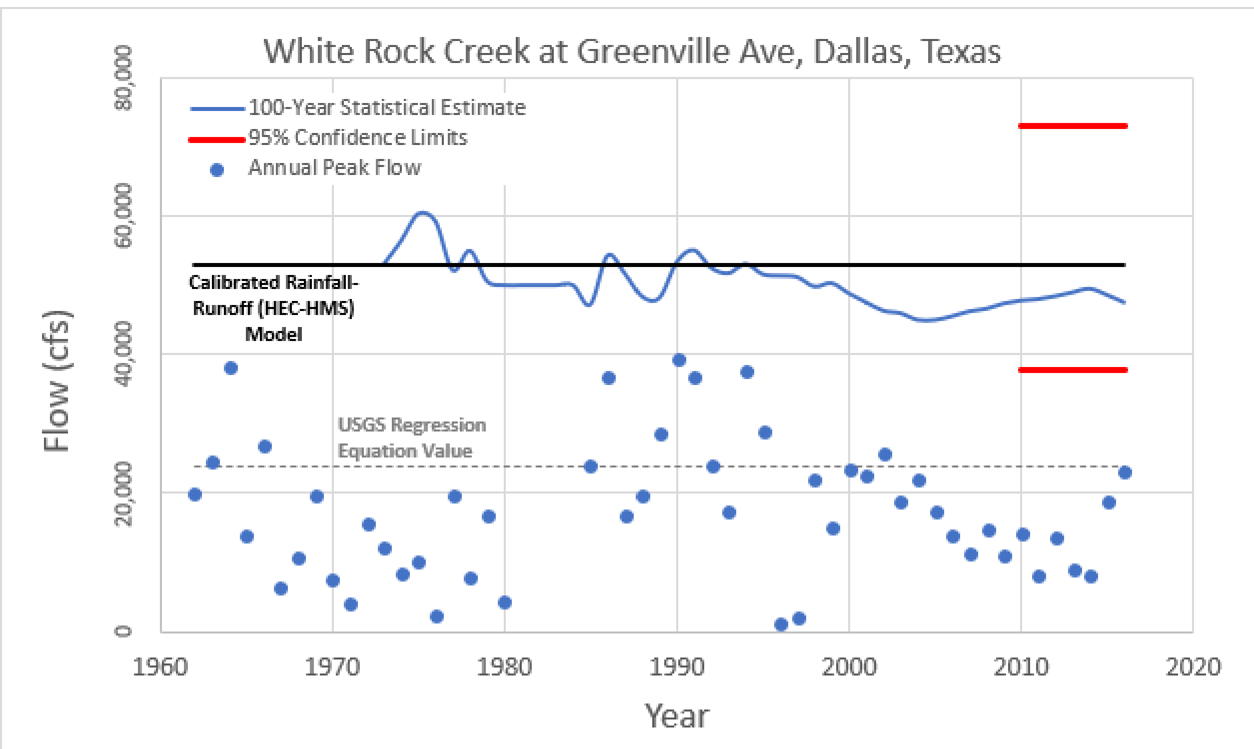


Figure 10.55 100-YR Flow Comparison for White Rock Creek at Greenville Ave, Dallas Gage

Table 10.43: Comparison of Frequency Flows at Trinity River below Honey Springs Branch (Below Dallas) Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	200,100	192,900	200,100	124,300		219,000	185,700	
0.004	200				103,100		167,800	143,800	
0.01	100	119,300	119,600	119,300	88,300		134,300	116,700	
0.02	50	96,500	93,600	96,500	74,500		103,500	90,000	
0.04	25		70,700	74,100	61,600		78,900	68,400	
0.1	10	54,700	47,200	54,700	45,800		51,400	48,300	
0.2	5			37,700	34,700		38,300	35,700	
0.5	2			22,300	20,200		23,400	21,900	

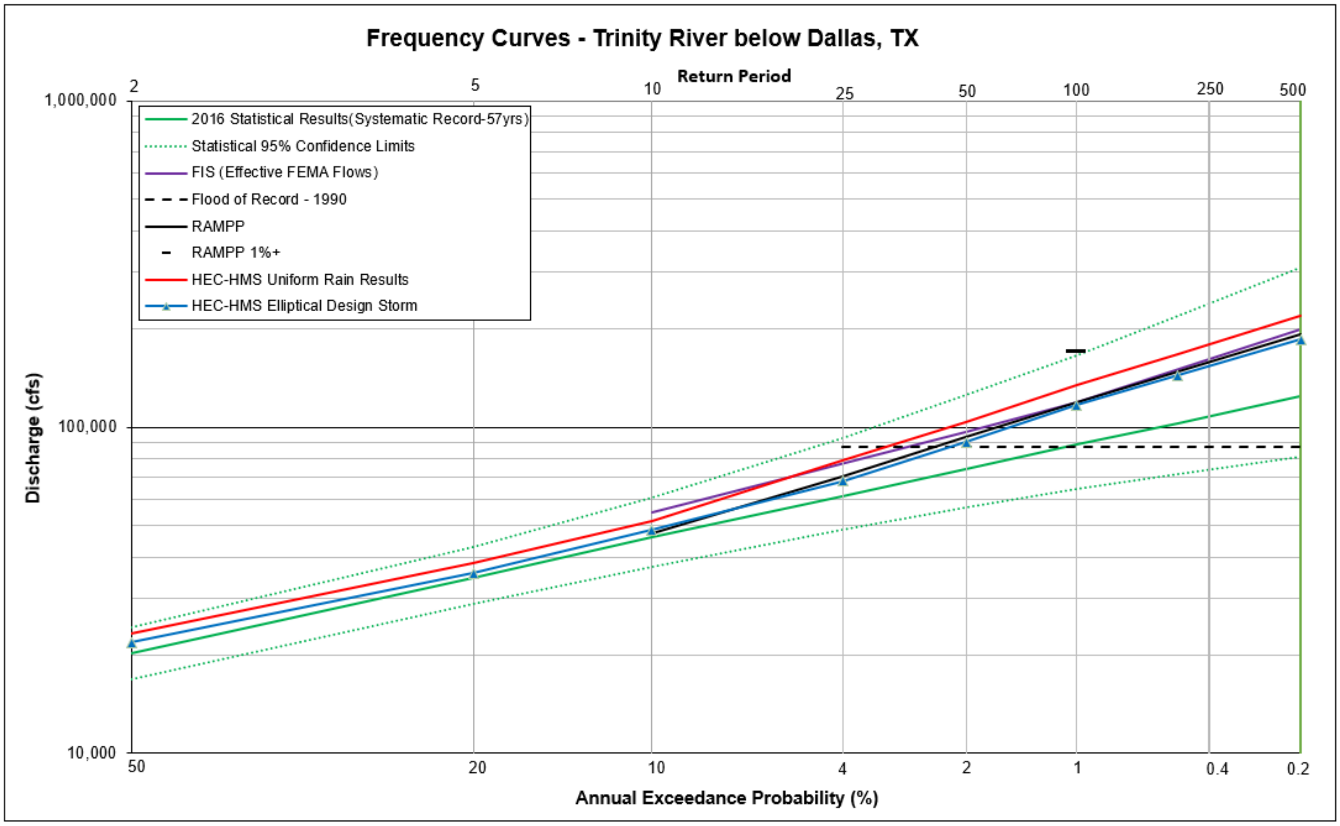


Figure 10.56: Flow Frequency Curve Comparison for Trinity River below Dallas Gage

Table 10.44: Comparison of Frequency Flows at Prairie Creek at Highway 175 Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	18,300		15,500	11,200				
0.004	200				9,200				
0.01	100	13,100		12,200	7,800				
0.02	50	11,100		10,800	6,600				
0.04	25				5,400				
0.1	10	7,500		7,700	4,100				
0.2	5				3,100				
0.5	2				1,900				

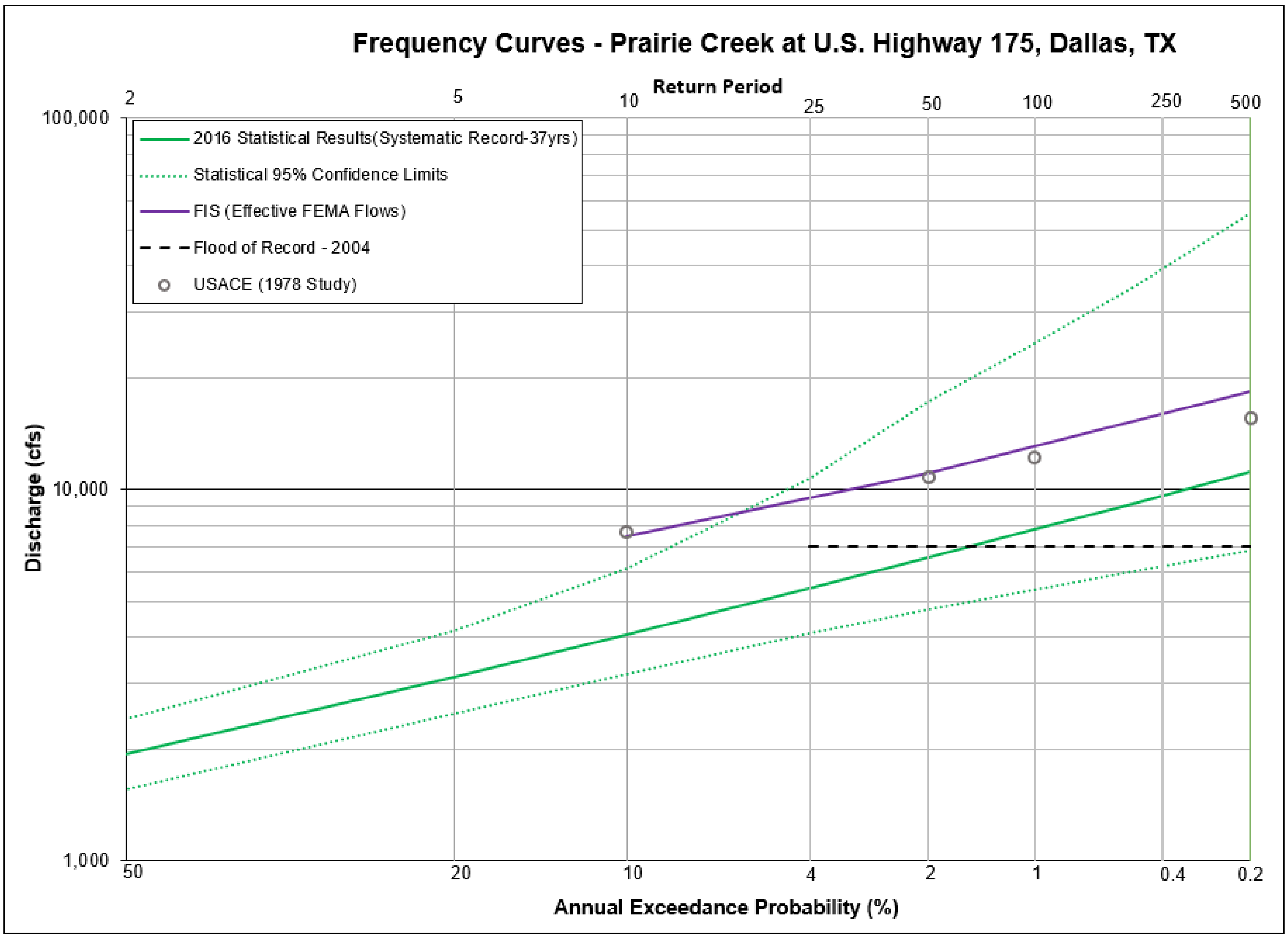


Figure 10.57: Flow Frequency Curve Comparison for Prairie Creek at U.S. Hwy 175, Dallas Gage

Table 10.45: Comparison of Frequency Flows at East Fork Trinity River near McKinney Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	77,700			48,000		51,400		
0.004	200				40,200		41,400		
0.01	100	51,400		49,700	34,400		33,800		
0.02	50	41,200		35,500	28,800		25,600		
0.04	25			24,900	23,300		19,300		
0.1	10	20,800		17,000	16,400		12,500		
0.2	5				11,500		8,500		
0.5	2			6,000	5,400		4,600		

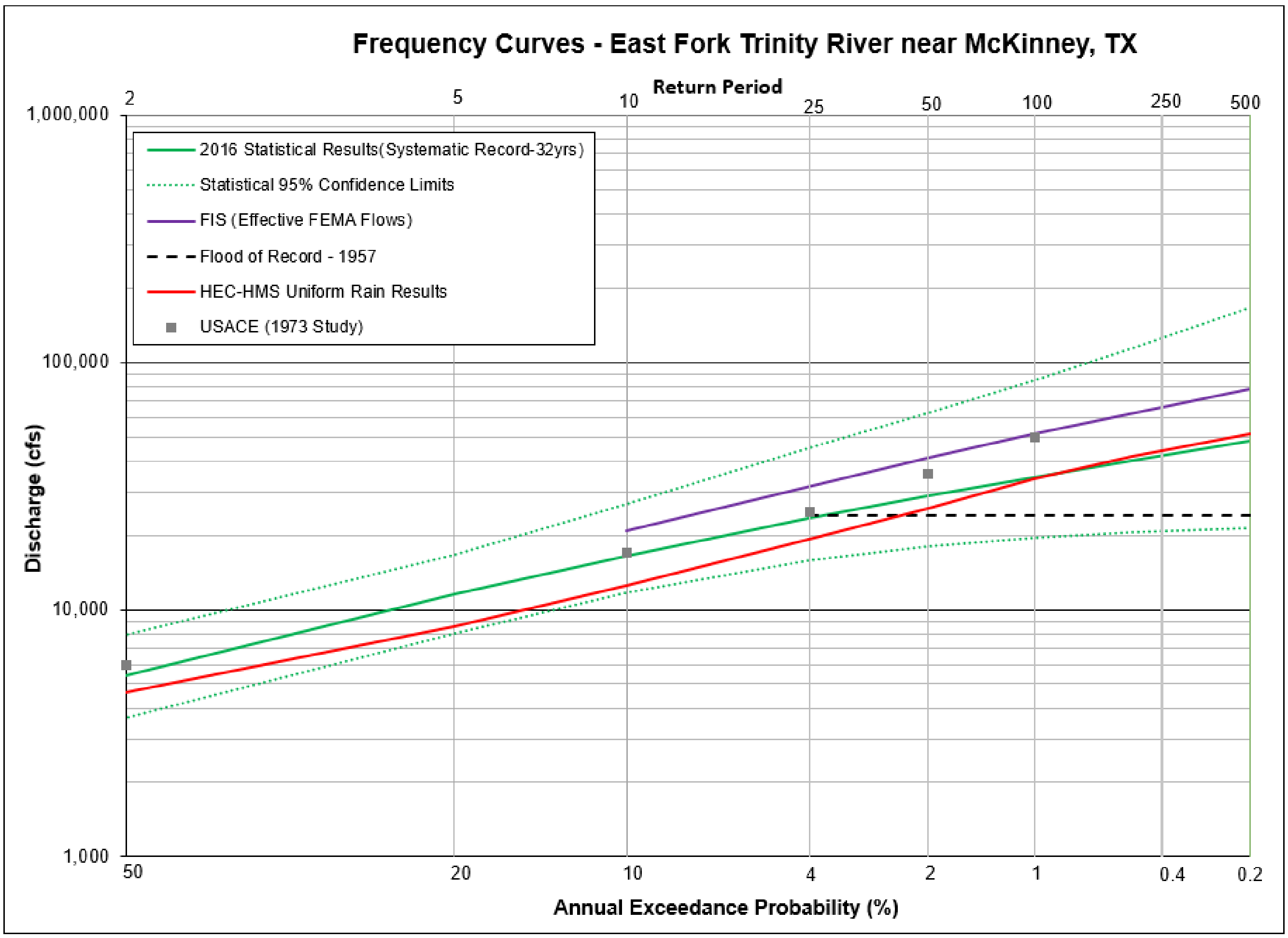


Figure 10.58: Flow Frequency Curve Comparison for East fork Trinity River near McKinney Gage

Table 10.46: Comparison of Frequency Flows at Sister Grove Creek near Blue Ridge Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				16,300		16,500		
0.004	200				12,900		13,400		
0.01	100				10,600		11,000		
0.02	50				8,600		8,400		
0.04	25				6,700		6,400		
0.1	10				4,600		4,100		
0.2	5				3,200		2,800		
0.5	2				1,600		1,400		

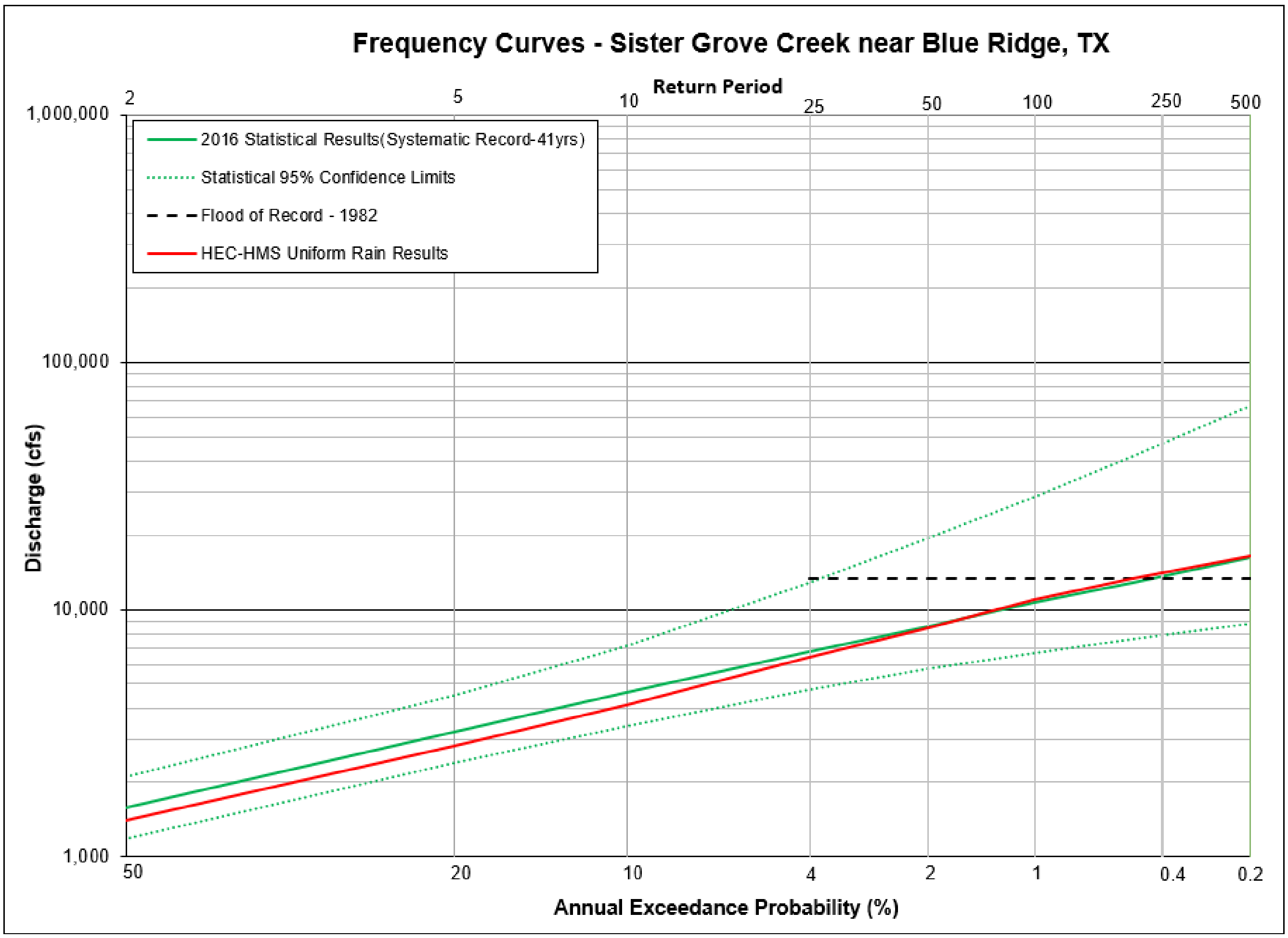


Figure 10.59: Flow Frequency Curve Comparison for Sister Grove Creek near Blue Ridge Gage

Table 10.47: Comparison of Frequency Flows for Lake Lavon Outflow

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500						51,800		66,000
0.004	200						24,800		49,300
0.01	100						14,600		35,200
0.02	50						6,200		22,000
0.04	25						0		10,700
0.1	10						0		8,000
0.2	5						0		8,000
0.5	2						0		4,000

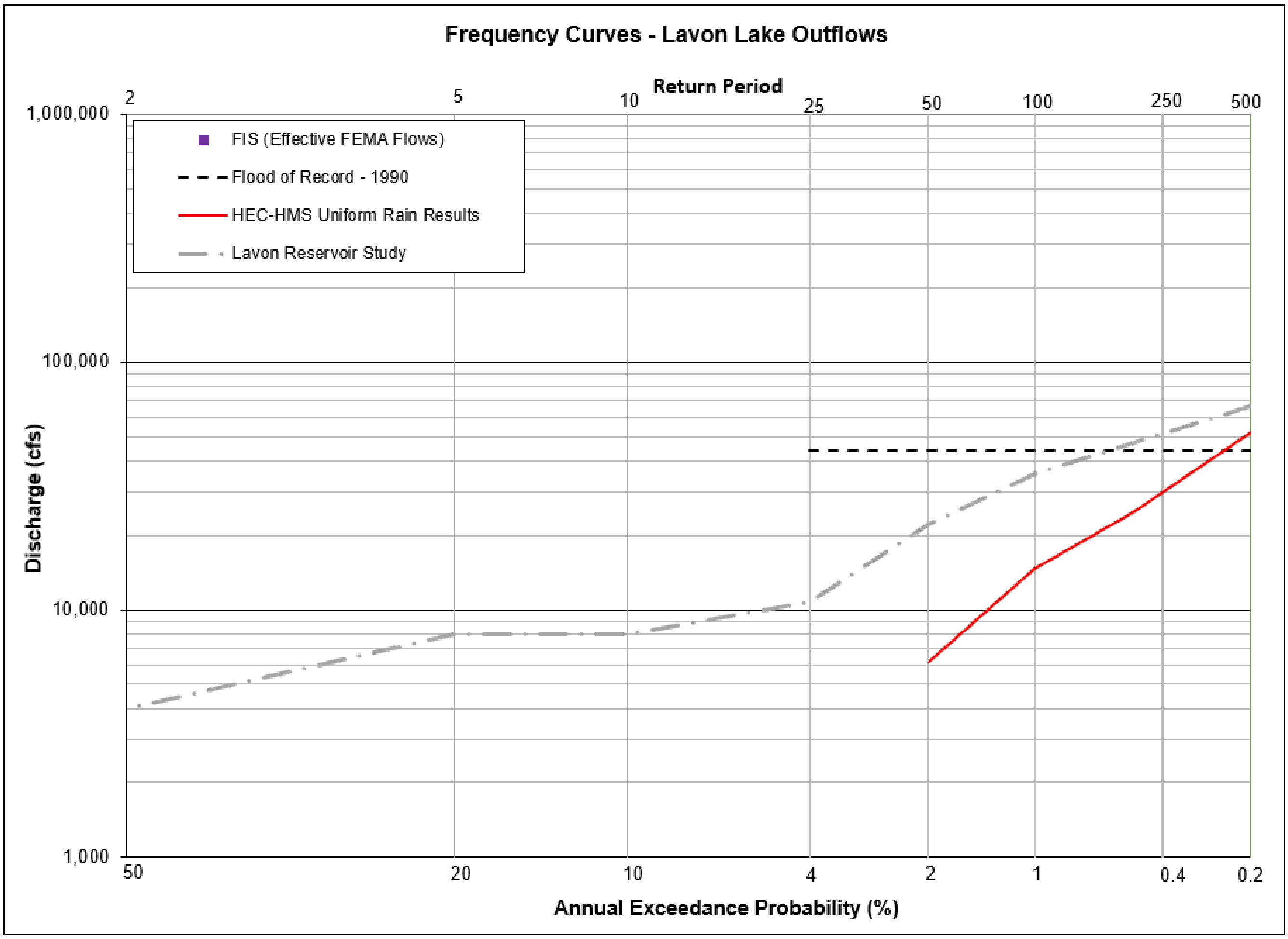


Figure 10.60: Flow Frequency Curve Comparison for Lavon Lake Outflow

Table 10.48: Comparison of Frequency Flows at Rowlett Creek near Sachse Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	81,500		82,200	77,800		83,800		
0.004	200				64,800		72,100		
0.01	100	61,200		61,100	55,400		63,600		
0.02	50	50,200		52,300	46,600		54,600		
0.04	25				38,100		46,600		
0.1	10	30,500		30,900	27,700		35,200		
0.2	5				20,200		25,400		
0.5	2			10,500	10,700		13,500		

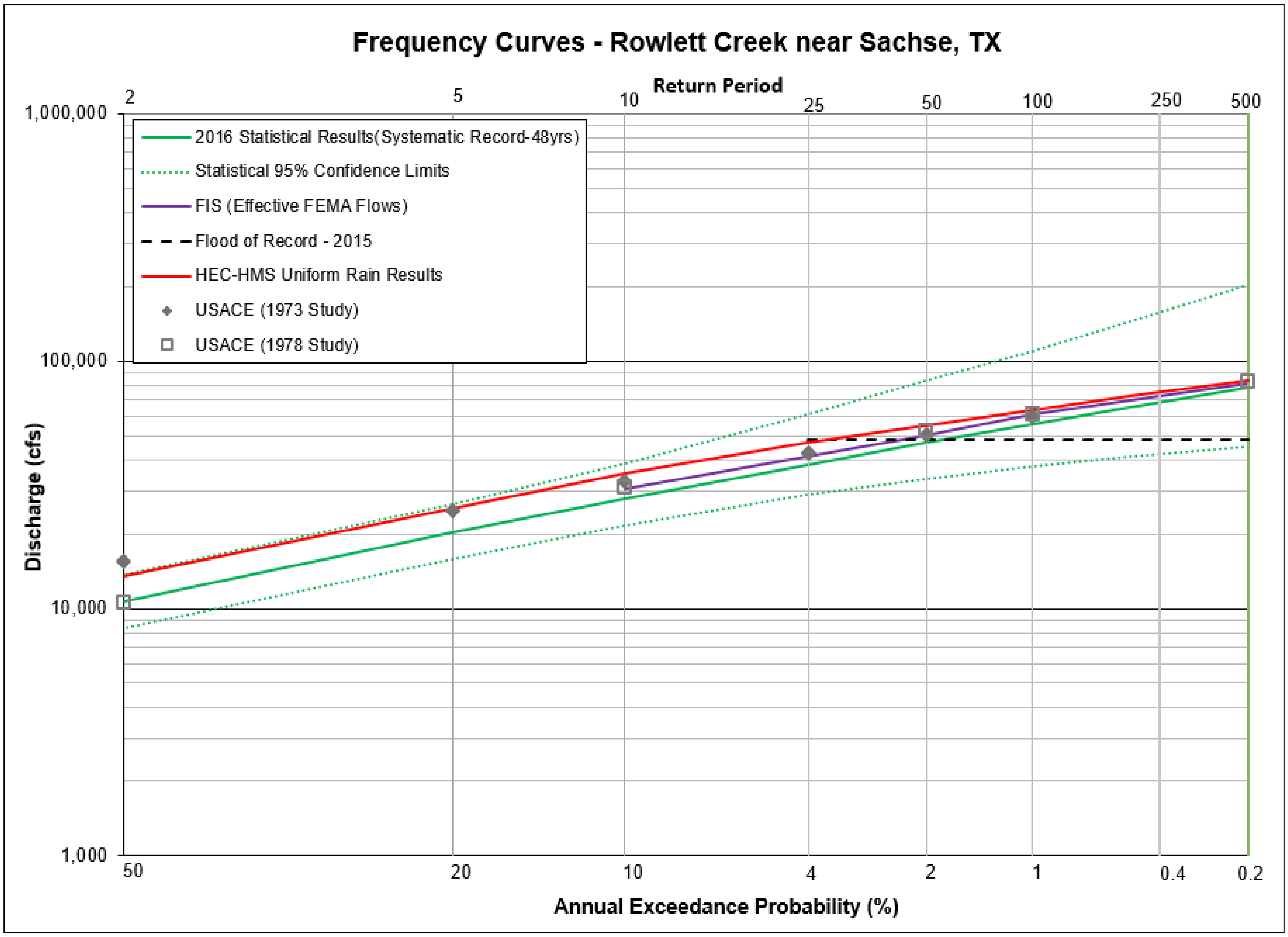


Figure 10.61: Flow Frequency Curve Comparison for Rowlett Creek near Sachse Gage

Figure 10.62 below provides a comparison between the 100-year calibrated rainfall-runoff model (HEC-HMS) results, observed annual peak flows, 100-year USGS regression equation results, and 100-year statistical hydrology results at the Rowlett Creek near Sachse USGS gage. The statistical hydrology results show how the 100-year statistical hydrology value has changed as each additional annual peak flow is added to the record. Generally, at least 300-400 years of record are needed before the 1% annual chance (100-yr) flow frequency estimates will stop significantly changing over time with additional years of record, unless additional information such as rainfall-runoff modeling estimates are utilized in the statistical analysis.

For this location, the HEC-HMS results have been both higher and lower than the statistical hydrology estimate as the statistical hydrology result has changed over time. The HEC-HMS results are well within the statistical hydrology 95% confidence limits and are higher than the statistical hydrology estimate using the full record length. It should be noted however that the largest event on record (2018) was not included in the statistical hydrology estimate which included peak flows through 2016. Including the 2018 peak flow would increase the statistical hydrology estimate to be more similar and possibly higher than the HEC-HMS 100-yr estimate. The HEC-HMS results are higher than the USGS regression equation value, which considers the drainage area below USACE reservoirs and other major reservoirs, and has been exceeded several times, likely due to the nearly fully urbanized condition of the watershed.

Because of these differences, additional investigation was performed. Rainfall analysis was performed on the 2018 event. This event produced the largest peak flow at this gage. This peak flow (57,000 cfs) resulted from about 7.4 inches of rainfall over 24-hours. This equates to somewhere between a 25-year to 50-year rainfall event. The 100-yr 24-hour NOAA Atlas 14 rainfall amount is 8.8 inches and resulted in an HEC-HMS peak flow of 63,600 cfs. While the 100-yr HEC-HMS results are higher than the statistical hydrology results and the regression equation results, based on comparison to observed rainfall events and the statistical hydrology changes that would result from incorporating the 2018 event, the 100-yr results from the HEC-HMS model is a reasonable estimate of the 100-yr flood event.

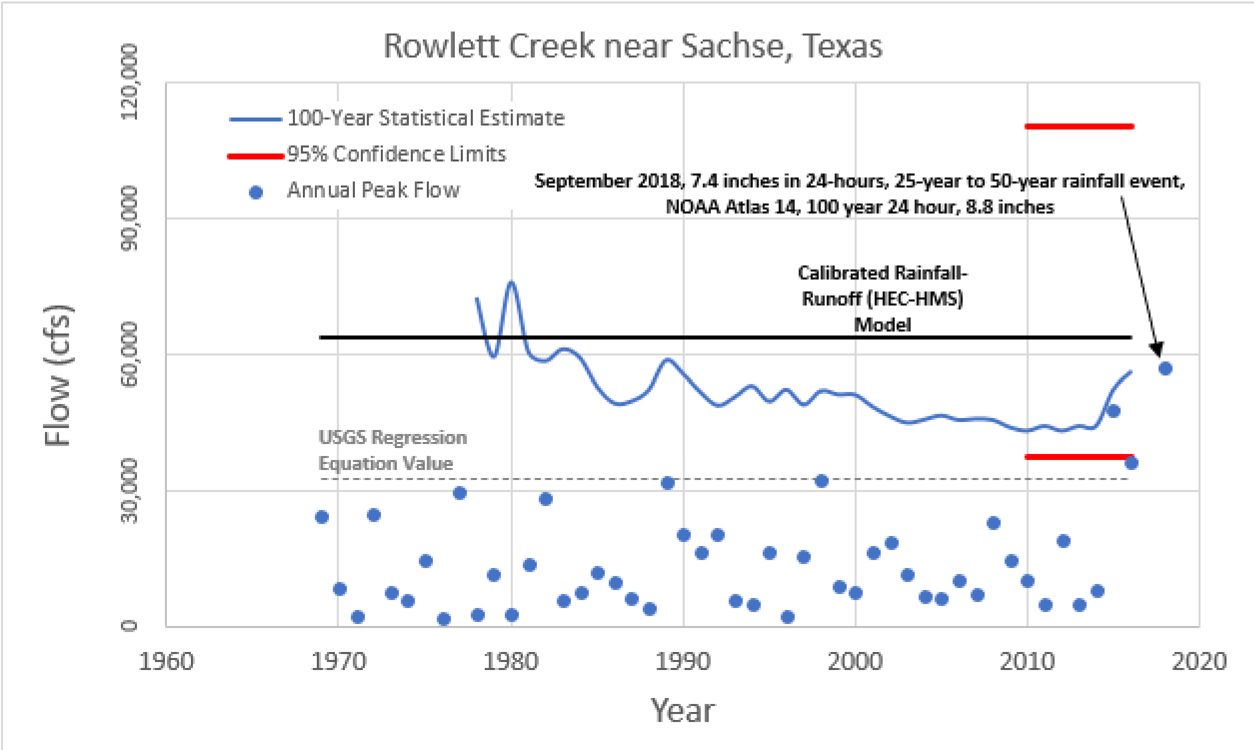


Figure 10.62 100-YR Flow Comparison for Rowlett Creek near Sachse Gage

Table 10.49: Comparison of Frequency Flows for Ray Hubbard Lake Outflow

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500						101,300		66,000
0.004	200						83,300		49,300
0.01	100	104,800					59,800		35,200
0.02	50						47,400		22,000
0.04	25						38,000		10,700
0.1	10						26,000		8,000
0.2	5						16,500		8,000
0.5	2						8,900		4,000

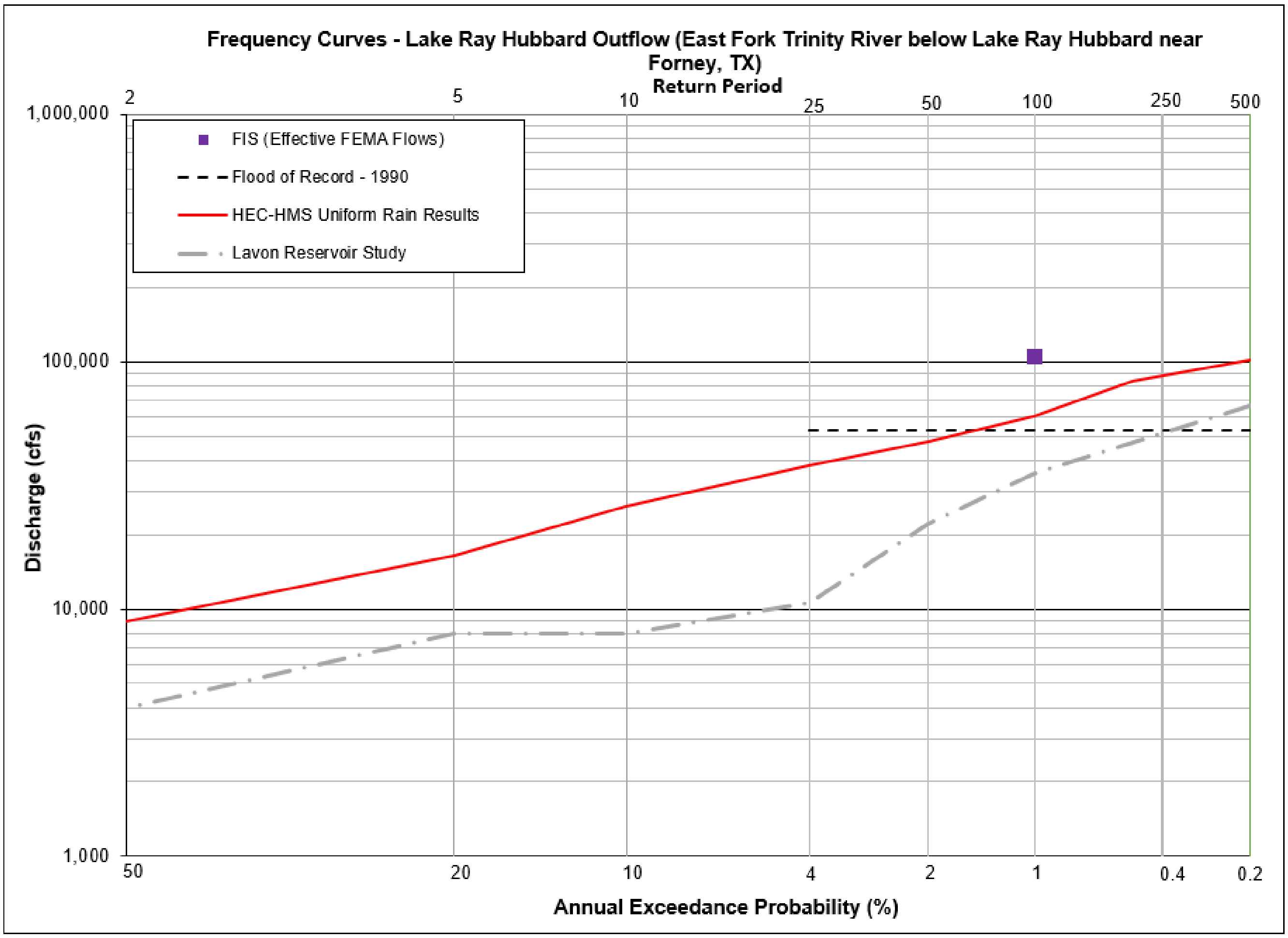


Figure 10.63: Flow Frequency Curve Comparison for Lake Ray Hubbard Outflow

Table 10.50: Comparison of Frequency Flows at East Fork Trinity River near Forney Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				69,900		117,100	113,800	
0.004	200				63,200		95,500	89,500	
0.01	100	101,700			57,600		69,300	65,900	
0.02	50				51,500		55,000	55,900	
0.04	25				44,700		44,100	47,200	
0.1	10				34,700		30,300	35,100	
0.2	5				26,300		19,500	25,700	
0.5	2				13,800		10,500	14,000	

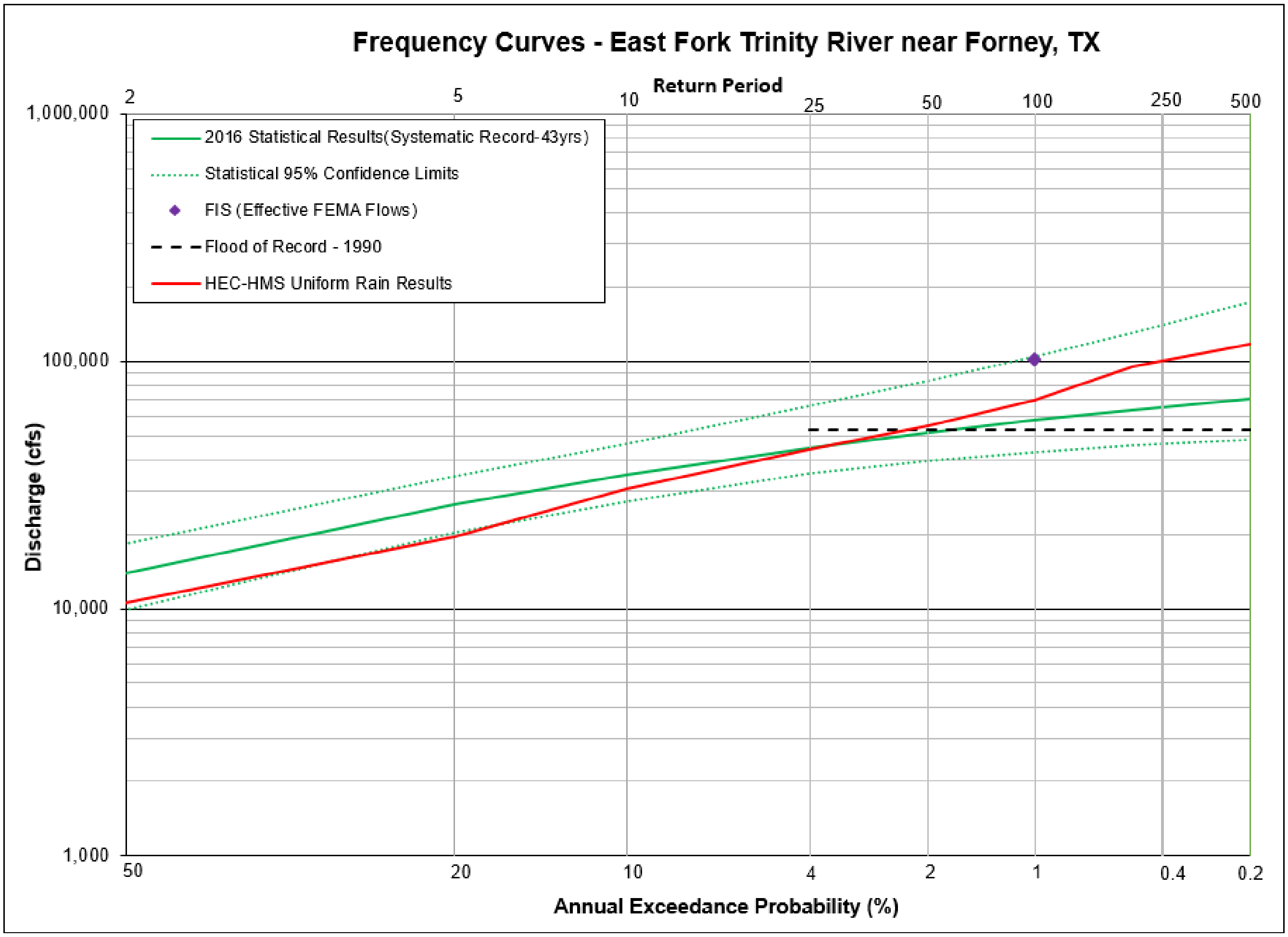


Figure 10.64: Flow Frequency Curve Comparison for East fork Trinity River near Forney Gage

Table 10.51: Comparison of Frequency Flows at East Fork Trinity River near Crandall Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				71,000	48,500	98,300	90,700	
0.004	200				60,100	40,800	73,900	68,100	
0.01	100				52,000	35,200	58,400	53,900	
0.02	50				44,100	29,900	44,300	44,600	
0.04	25				36,400	23,100	33,200	35,800	
0.1	10				26,500	18,100	23,500	26,500	
0.2	5				19,200	13,400	15,500	19,400	
0.5	2				9,800	7,200	8,200	9,600	

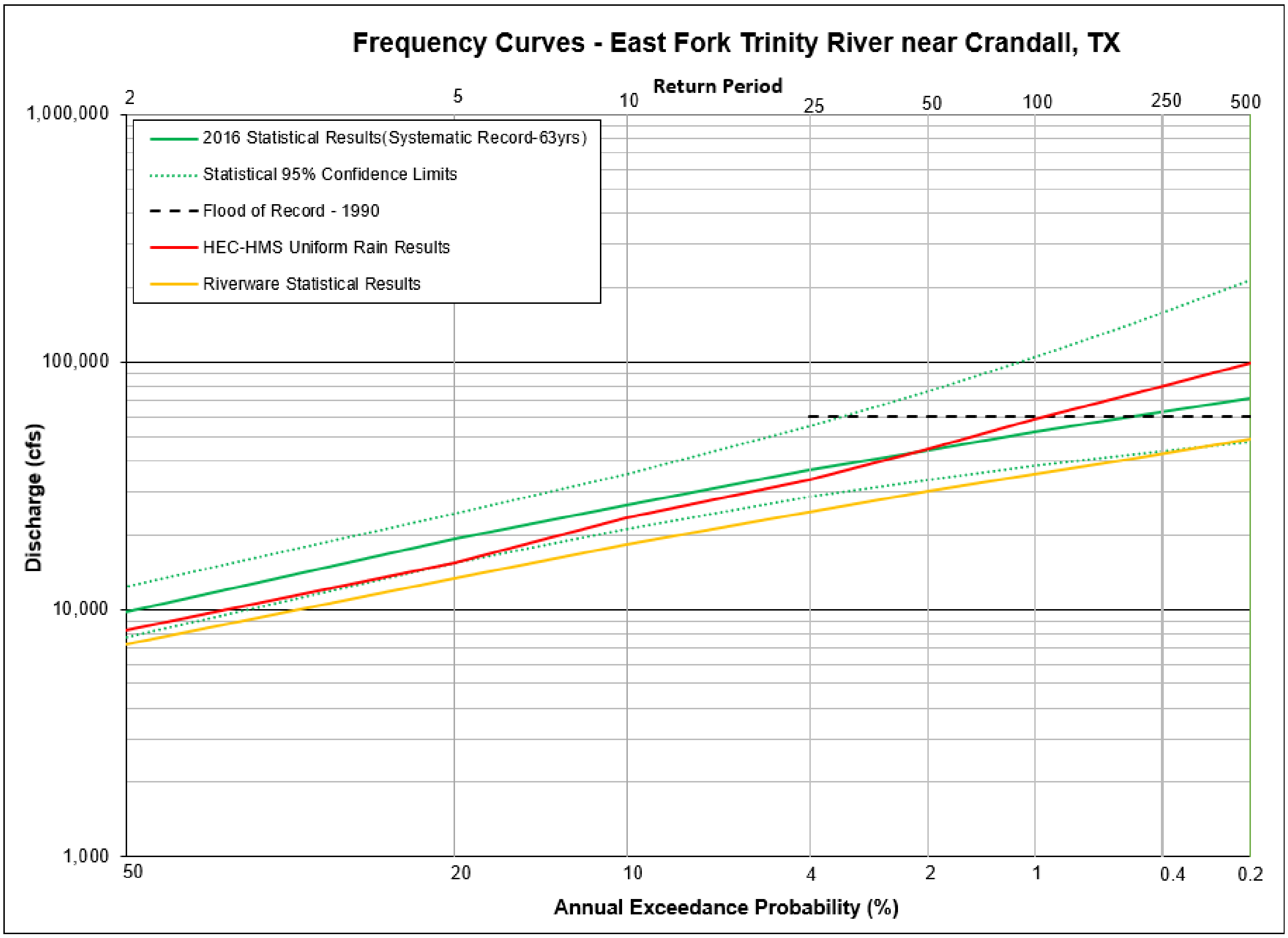


Figure 10.65: Flow Frequency Curve Comparison for East Fork Trinity River near Crandall Gage

Figure 10.66 below provides a comparison between the 100-year calibrated rainfall-runoff model (HEC-HMS) results, observed annual peak flows, 100-year USGS regression equation results, and 100-year statistical hydrology results at the East Fork Trinity River near Crandall USGS gage. The statistical hydrology results show how the 100-year statistical hydrology value has changed as each additional annual peak flow is added to the record. Generally, at least 300-400 years of record are needed before the 1% annual chance (100-yr) flow frequency estimates will stop significantly changing over time with additional years of record, unless additional information such as rainfall-runoff modeling estimates are utilized in the statistical analysis.

For this location, the HEC-HMS results have been both higher and lower than the statistical hydrology estimate as the statistical hydrology result has changed over time. The HEC-HMS results are well within the statistical hydrology 95% confidence limits and are similar to the statistical hydrology estimate using the full record length. The HEC-HMS results are higher than the USGS regression equation value, which considers the drainage area below USACE reservoirs and other major reservoirs. The HEC-HMS results and statistical hydrology estimate are very similar to the largest event which occurred in May 1990.

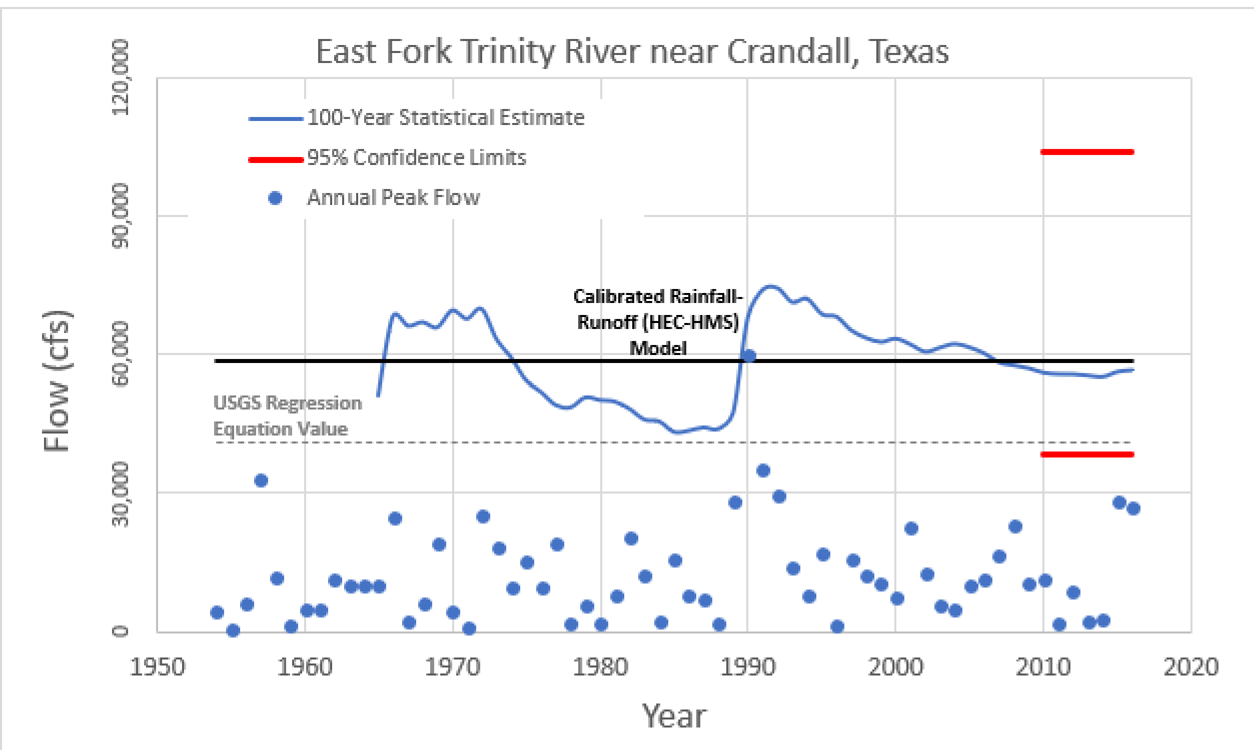


Figure 10.66 100-Y Flow Comparison East Fork Trinity River near Crandall Gage

Table 10.52: Comparison of Frequency Flows at Trinity River near Rosser Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				160,400	147,400	253,900	207,300	
0.004	200				133,700	121,200	200,800	164,600	
0.01	100				114,900	103,000	166,200	131,500	
0.02	50				97,100	86,100	126,100	98,700	
0.04	25				80,400	65,700	91,600	74,000	
0.1	10				59,600	51,500	54,900	51,000	
0.2	5				44,800	38,200	40,600	38,900	
0.5	2				25,500	21,400	27,200	25,600	

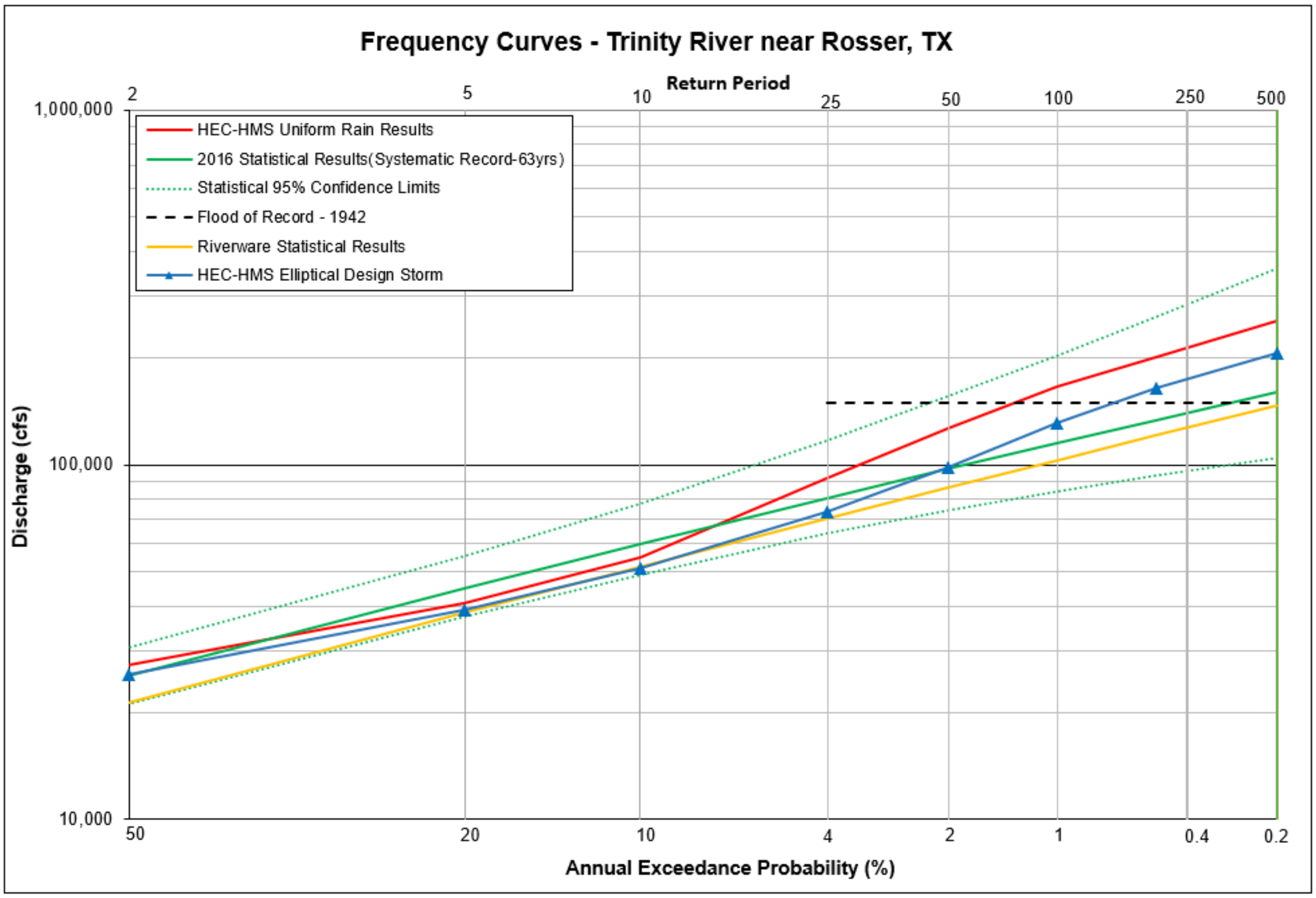


Figure 10.67: Flow Frequency Curve Comparison for Trinity River near Rosser Gage

Figure 10.68 below provides a comparison between the 100-year calibrated rainfall-runoff model (HEC-HMS) results, observed annual peak flows, 100-year USGS regression equation results, and 100-year statistical hydrology results at the Trinity River near Rosser USGS gage. The statistical hydrology results show how the 100-year statistical hydrology value has changed as each additional annual peak flow is added to the record. Generally, at least 300-400 years of record are needed before the 1% annual chance (100-yr) flow frequency estimates will stop significantly changing over time with additional years of record, unless additional information such as rainfall-runoff modeling estimates are utilized in the statistical analysis.

For this location, the HEC-HMS results have been both higher and lower than the statistical hydrology estimate as the statistical hydrology result has changed over time. The HEC-HMS results are well within the statistical hydrology 95% confidence limits and are higher than the statistical hydrology estimate using the full record length. The HEC-HMS results are lower than the USGS regression equation value, which considers the drainage area below USACE reservoirs and other major reservoirs.

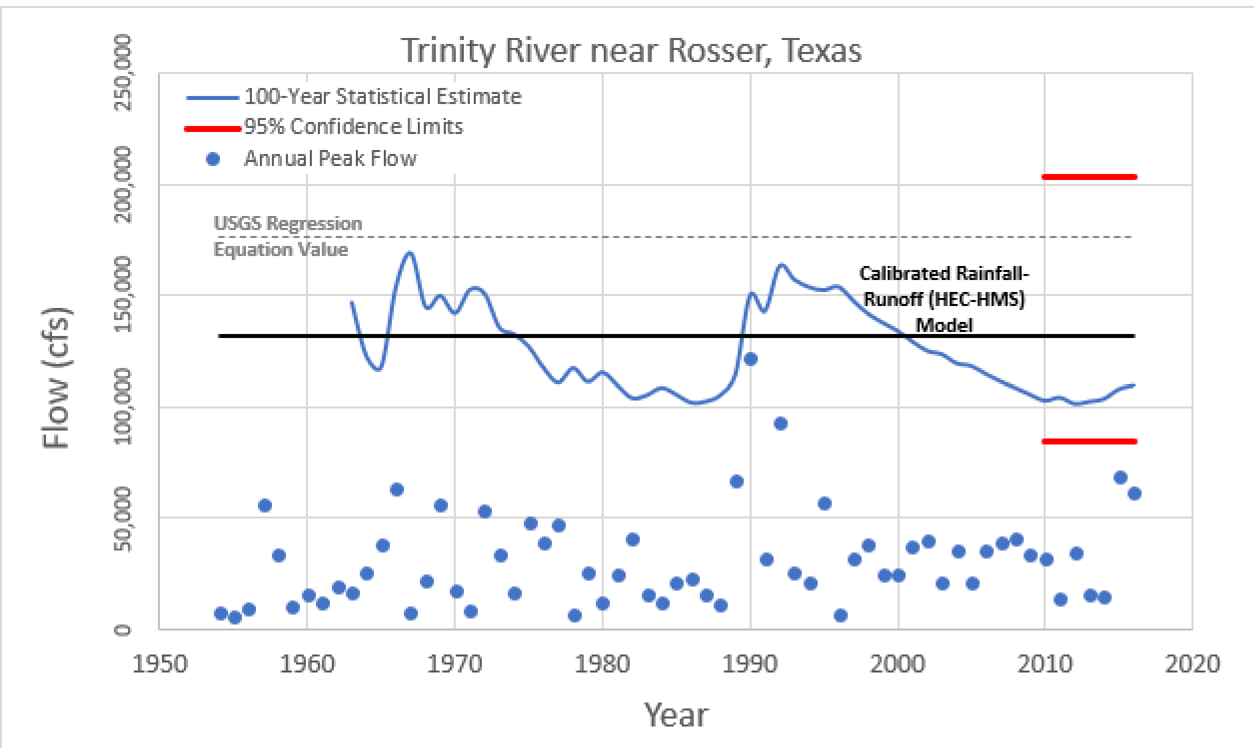


Figure 10.68 100-YR Flow Comparison for Trinity River near Rosser Gage

Table 10.53: Comparison of Frequency Flows at Trinity River at Trinidad Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				133,900	137,200	286,400	188,200	
0.004	200				118,600	117,100	209,900	155,800	
0.01	100				106,800	102,200	168,400	125,100	
0.02	50				94,800	87,800	112,400	106,800	
0.04	25				82,600	69,100	86,700	89,100	
0.1	10				65,900	55,300	59,800	68,000	
0.2	5				52,600	41,800	43,300	51,200	
0.5	2				32,800	23,400	28,000	33,300	

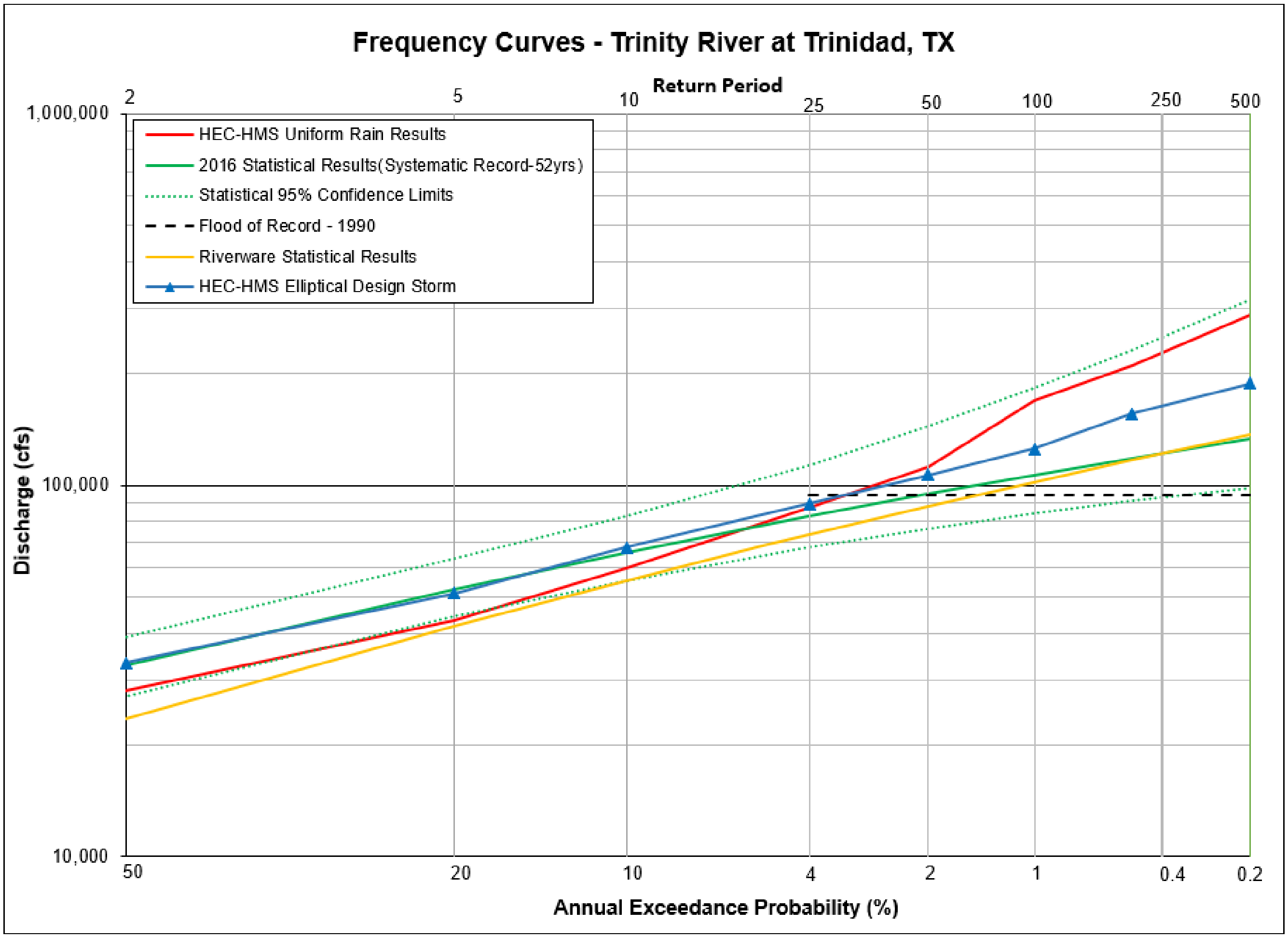


Figure 10.69: Flow Frequency Curve Comparison for Trinity River at Trinidad Gage

Table 10.54: Comparison of Frequency Flows at Cedar Creek near Kemp Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				30,900		34,100		
0.004	200				26,900		27,100		
0.01	100				23,800		22,200		
0.02	50				20,700		17,100		
0.04	25				17,500		14,600		
0.1	10				13,300		10,900		
0.2	5				10,100		8,400		
0.5	2				5,600		5,400		

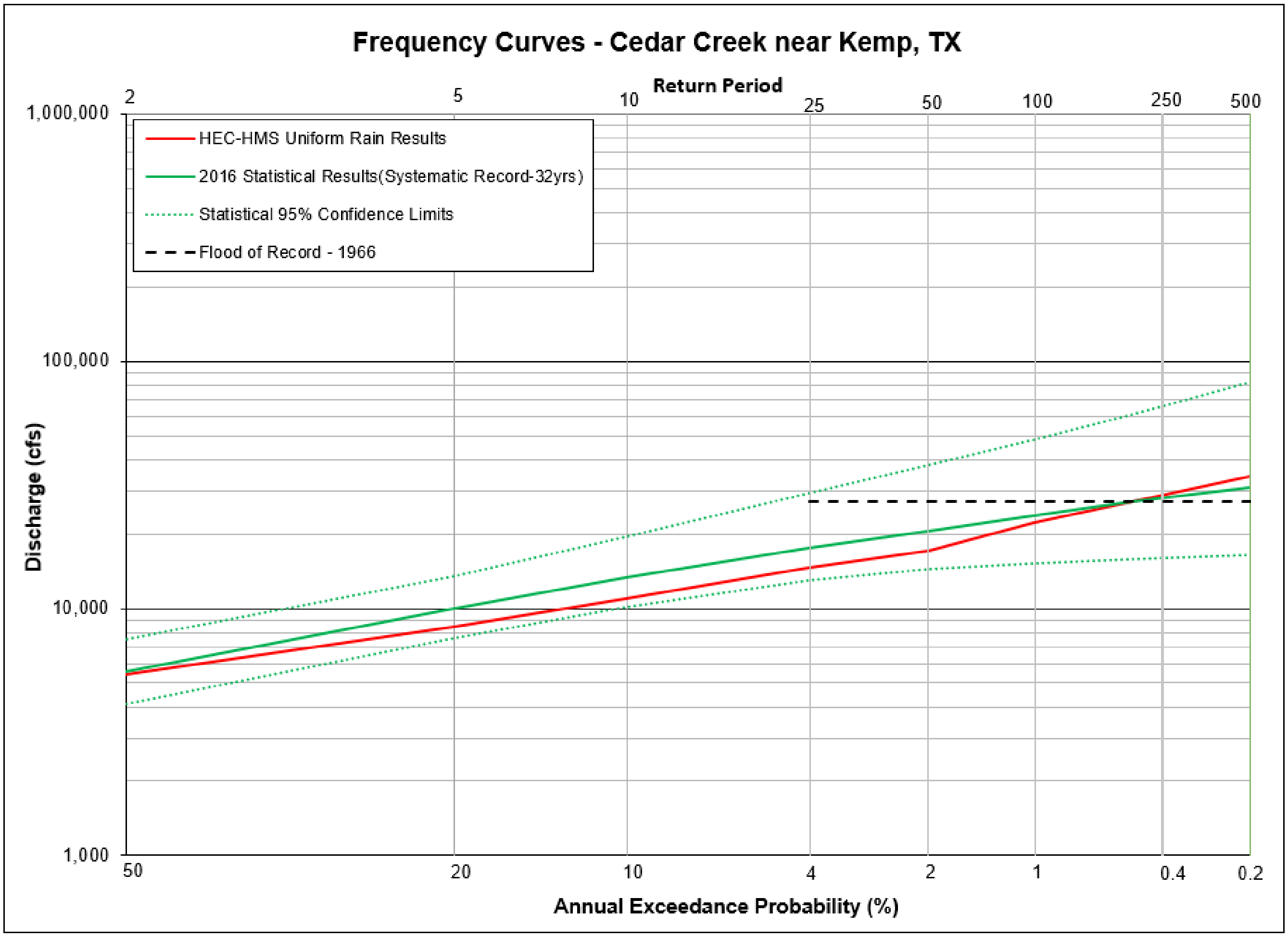


Figure 10.70: Flow Frequency Curve Comparison for Cedar Creek near Kemp Gage

Table 10.55: Comparison of Frequency Flows at Kings Creek at SH34 near Kaufman Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500						39,500		
0.004	200						31,500		
0.01	100	46,800					25,900		
0.02	50						19,900		
0.04	25						15,300		
0.1	10						10,500		
0.2	5						7,400		
0.5	2						3,800		

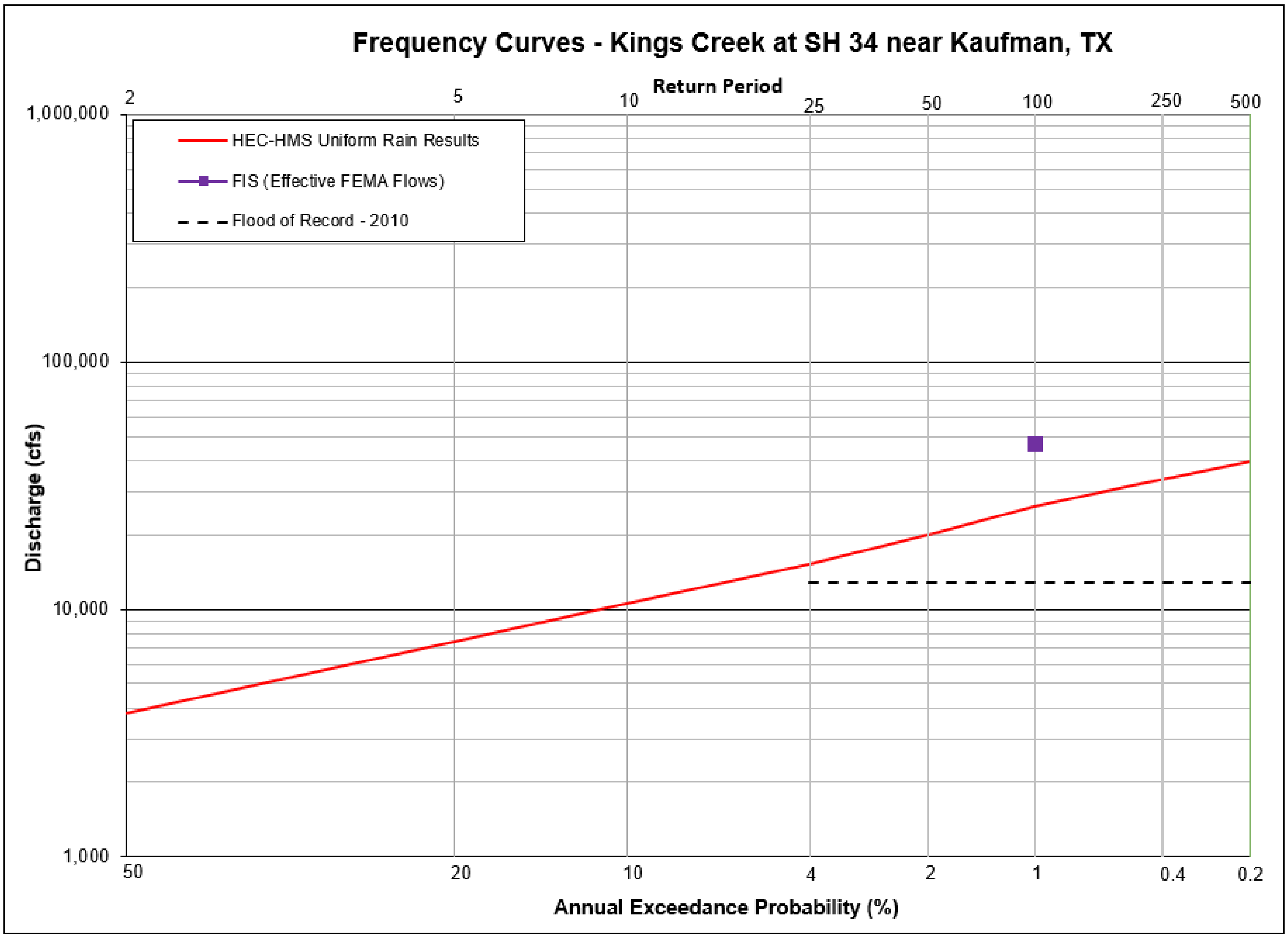


Figure 10.71: Flow Frequency Curve Comparison for Kings Creek at SH 34 near Kaufman Gage

Table 10.56: Comparison of Frequency Flows for Navarro Mills Lake Outflow

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis (Navarro Mills)
0.002	500				8,200		15,000		21,000
0.004	200				7,000		8,200		14,000
0.01	100				6,100		4,800		9,900
0.02	50				5,300		1,400		7,000
0.04	25				4,500		0		3,000
0.1	10				3,500		0		2,000
0.2	5				2,700		0		2,000
0.5	2				1,700		0		1,000

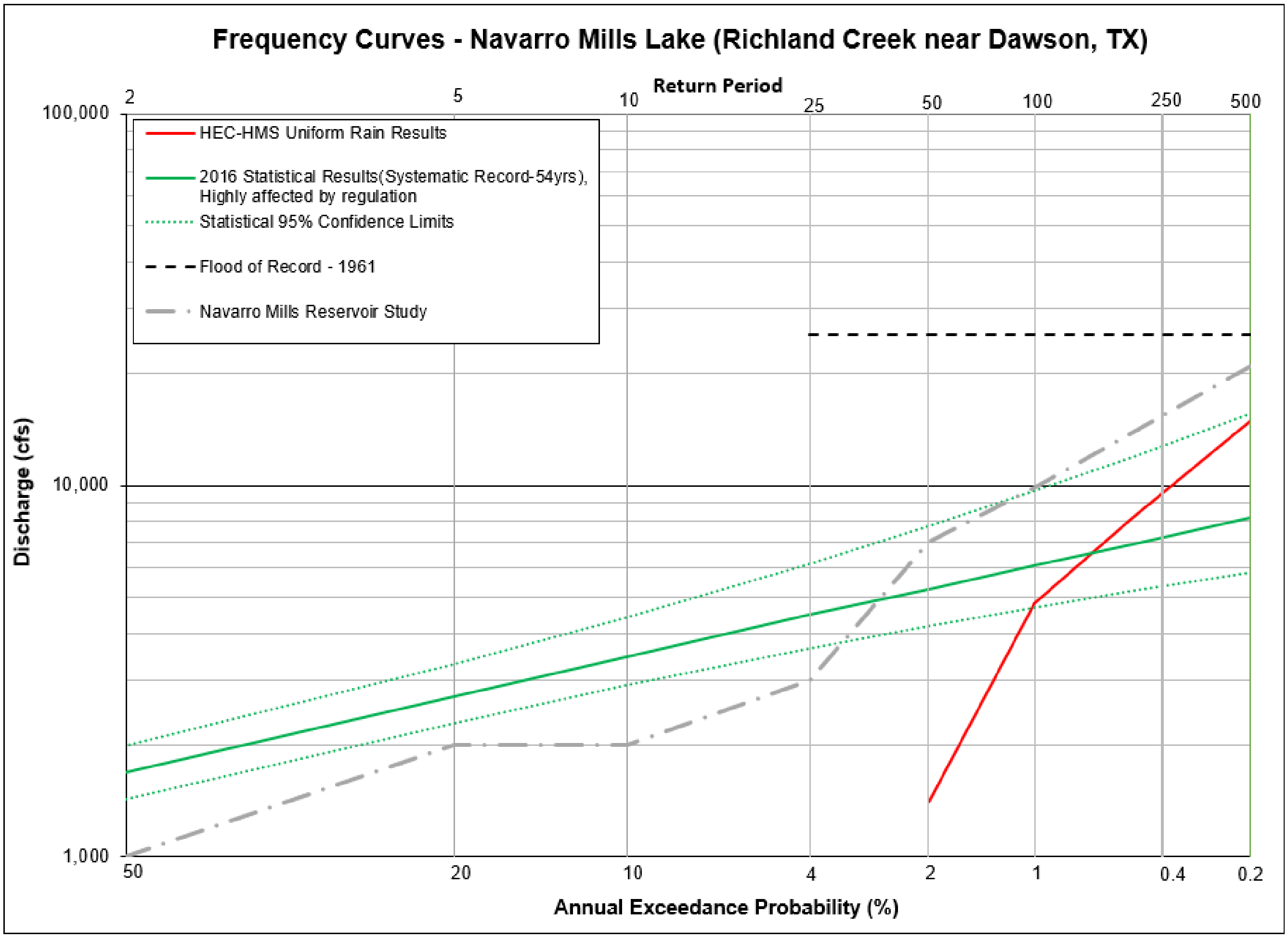


Figure 10.72: Flow Frequency Curve Comparison for Navarro Mills Lake Outflow

Table 10.57: Comparison of Frequency Flows at Waxahachie Creek at Waxahachie Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	24,600			25,900		42,800		
0.004	200				19,700		34,000		
0.01	100	15,000			15,700		27,500		
0.02	50	13,100			12,200		20,900		
0.04	25				9,100		15,500		
0.1	10	9,200			5,800		8,900		
0.2	5				3,700		4,400		
0.5	2				1,600		1,500		

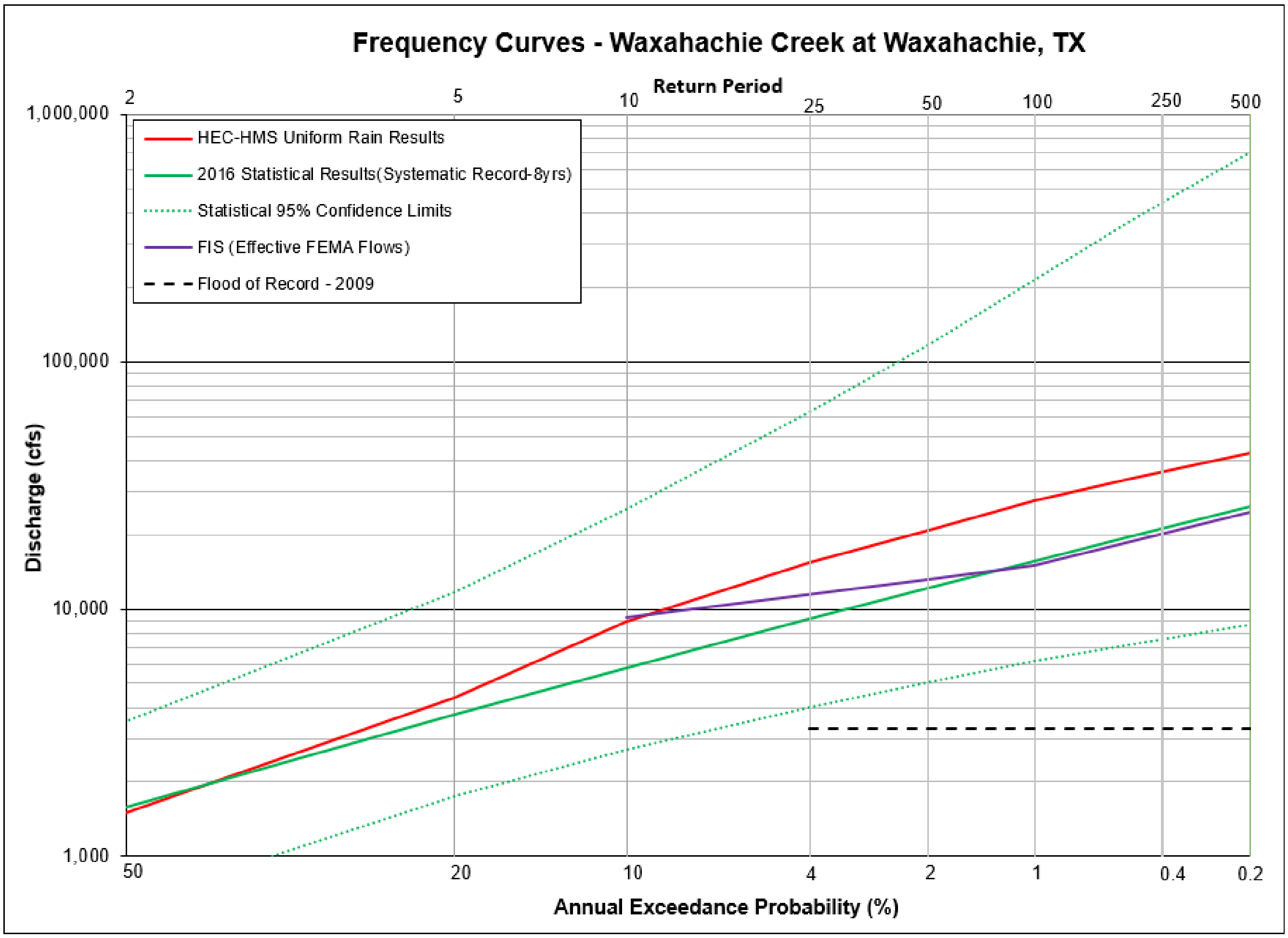


Figure 10.73: Flow Frequency Curve Comparison for Waxahachie Creek at Waxahachie Gage

Table 10.58: Comparison of Frequency Flows for Bardwell Lake Outflow

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				3,800		14,300		9,500
0.004	200				3,400		10,600		5,700
0.01	100				3,100		8,000		4,300
0.02	50				2,700		5,400		2,000
0.04	25				2,400		3,500		2,000
0.1	10				2,000		1,100		2,000
0.2	5				1,600		0		2,000
0.5	2				1,100		0		1,200

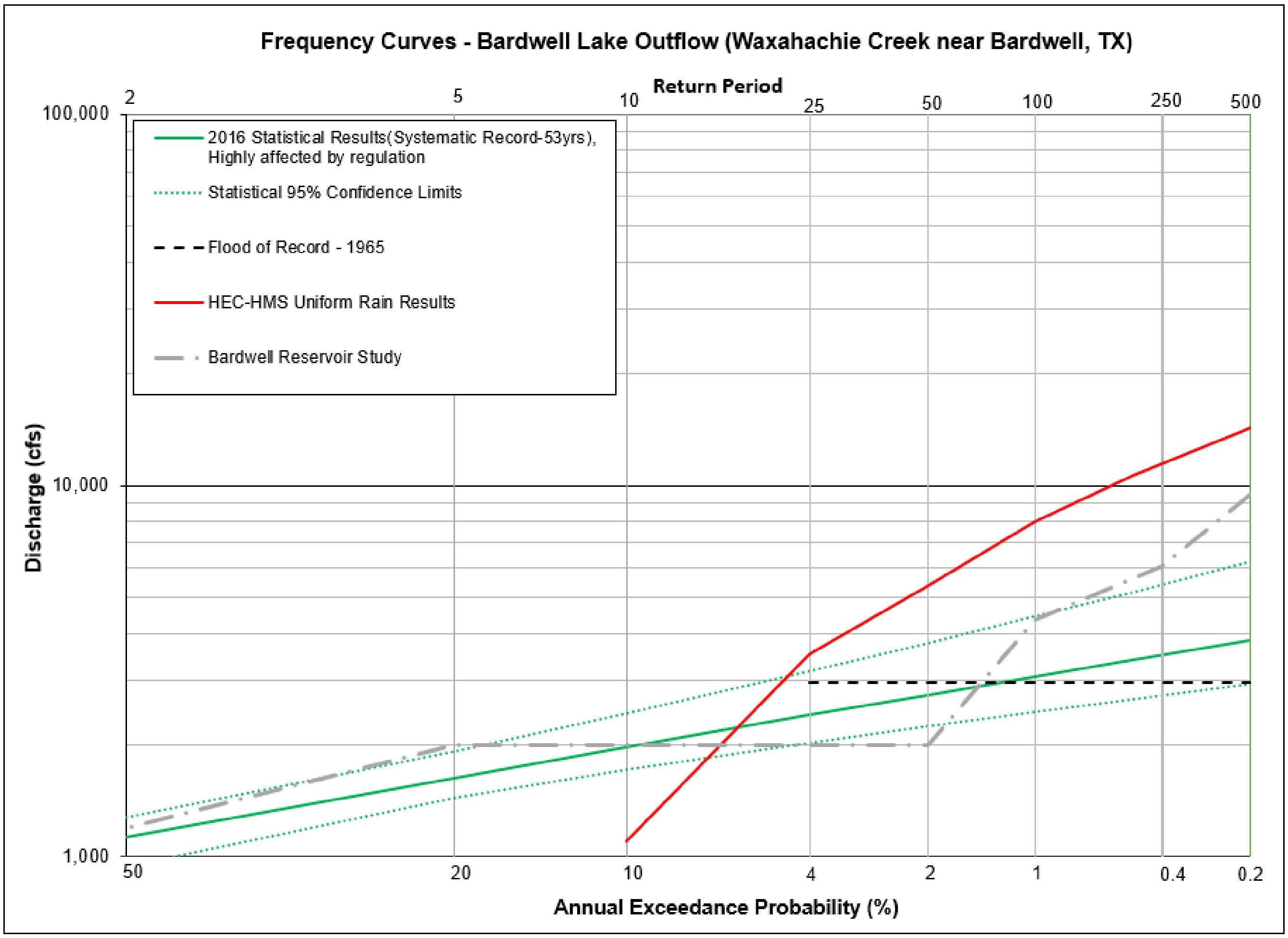


Figure 10.74: Flow Frequency Curve Comparison for Bardwell Lake Outflow

Table 10.59: Comparison of Frequency Flows at Chambers Creek near Rice Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				99,900	61,000	159,000	148,800	
0.004	200				82,000	52,900	119,500	110,500	
0.01	100				69,400	46,800	90,900	88,100	
0.02	50				57,500	40,600	65,600	73,300	
0.04	25				46,500	32,400	46,200	59,200	
0.1	10				33,000	26,200	29,900	39,000	
0.2	5				23,700	19,800	21,300	28,000	
0.5	2				12,100	10,900	11,200	12,500	

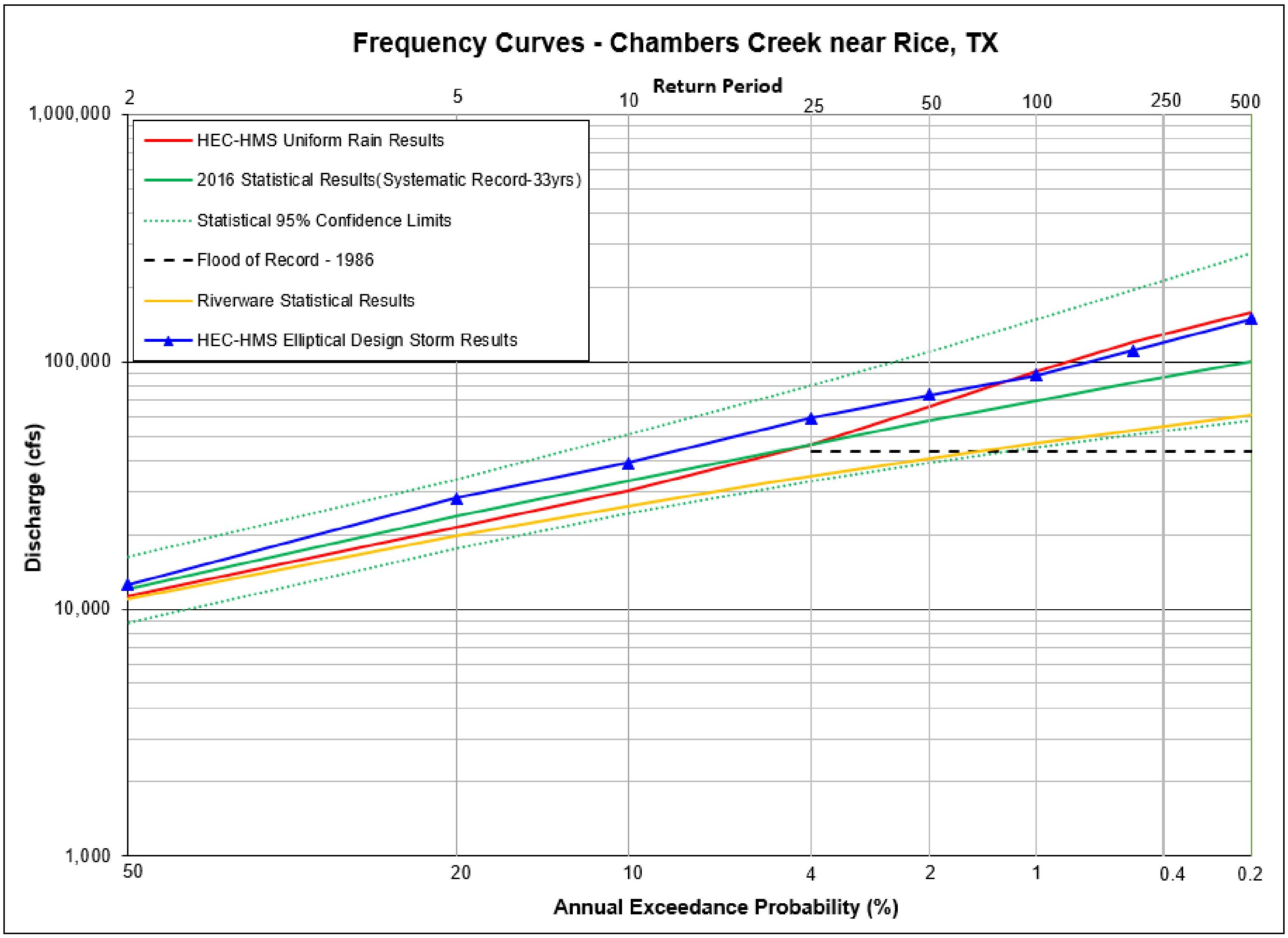


Figure 10.75: Flow Frequency Curve Comparison for Chambers Creek near Rice Gage

Table 10.60: Comparison of Frequency Flows for Richland-Chambers Reservoir Outflow

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500						234,700	193,900	193,000
0.004	200						177,300	143,200	141,200
0.01	100						136,200	107,400	111,300
0.02	50						93,800	86,000	91,800
0.04	25						63,700	65,800	62,600
0.1	10						34,300	42,700	37,400
0.2	5						21,600	26,700	25,900
0.5	2						10,200	9,500	13,100

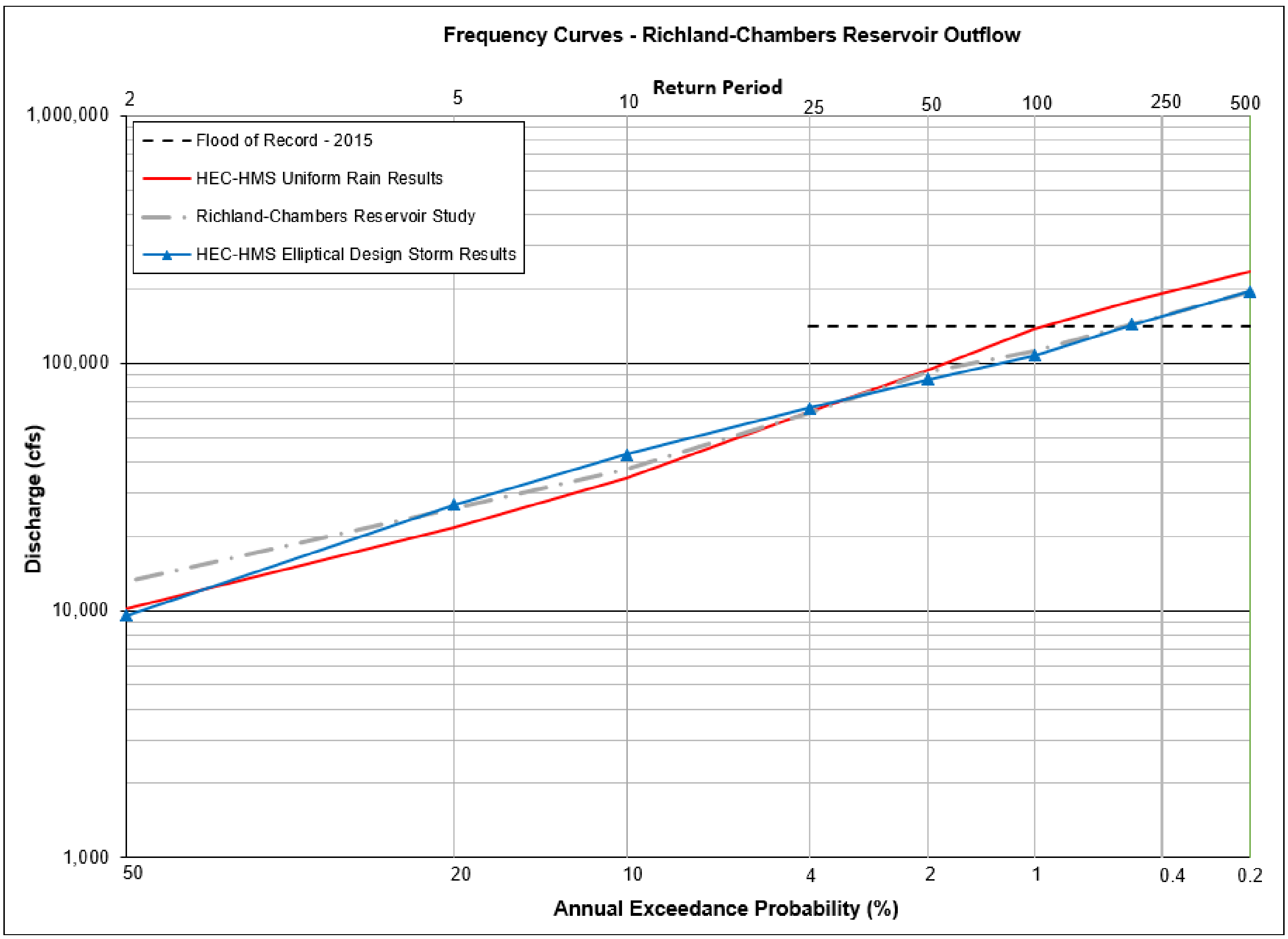


Figure 10.76: Flow Frequency Curve Comparison for Richland-Chambers Reservoir Outflow

For Tehuacana Creek near Streetman, there is no existing FIS information or other previous study to compare to. The HEC-HMS results are lower than the statistical hydrology results based on 48 years of systematic record. With nearly 50 years of systematic record, this has a moderate record length relative to other gages in the basin; However, there is still a large amount of uncertainty in the statistical estimates more rare than about the 10-yr recurrence interval (Section 5.3).

The statistical hydrology results appear to be overestimating the flow frequency estimates when comparing with HEC-HMS results from the USACE Fort Worth District Urban Curve equations for lag times. Utilizing these equations and assuming a 100% Urbanzied Watershed, the 1% annual chance event would only come out to 107,000 cfs, while the statistical hydrology estimate is 150,900 cfs. The velocity at which water would have to runoff to produce a peak discharge greater than 107,000 does not seem to make physical sense for this watershed.

In addition, the largest annual peak flow recorded at this gage was estimated at 85,700 cfs, whereas the largest flow measurement ever made at this site was only 48,100 cfs. In fact, the USGS has only been able to make four flow measurements at this site in the past 40 years that exceeded 10,000 cfs. Of those measurements, three were noted as “fair” and one was noted as “poor.” This means that there is likely considerable uncertainty in the USGS discharge estimates greater than 10,000 cfs at this location.

The final reason the statistical hydrology estimate appears to be overestimated is by comparison of the USGS rating curve with HEC-RAS models utilizing high quality terrain. HEC-RAS models indicate that for the recorded USGS annual peak stages, lower discharges should have been assigned. For example, the 1989 flood of record appears to have been closer to 50,000 cfs than the official 85,700 cfs. The figure below shows the USGS rating curve as being significantly flatter than that of the HEC-RAS model. Sensitivity analysis showed that regardless or roughness value choice within the HEC-RAS model, the USGS rating curve appears to be overestimating the discharges for a given stage. The net effect of this on the statistical frequency curve would be an overestimation of the annual peak discharges and thus overestimation of flood frequency estimates over time.

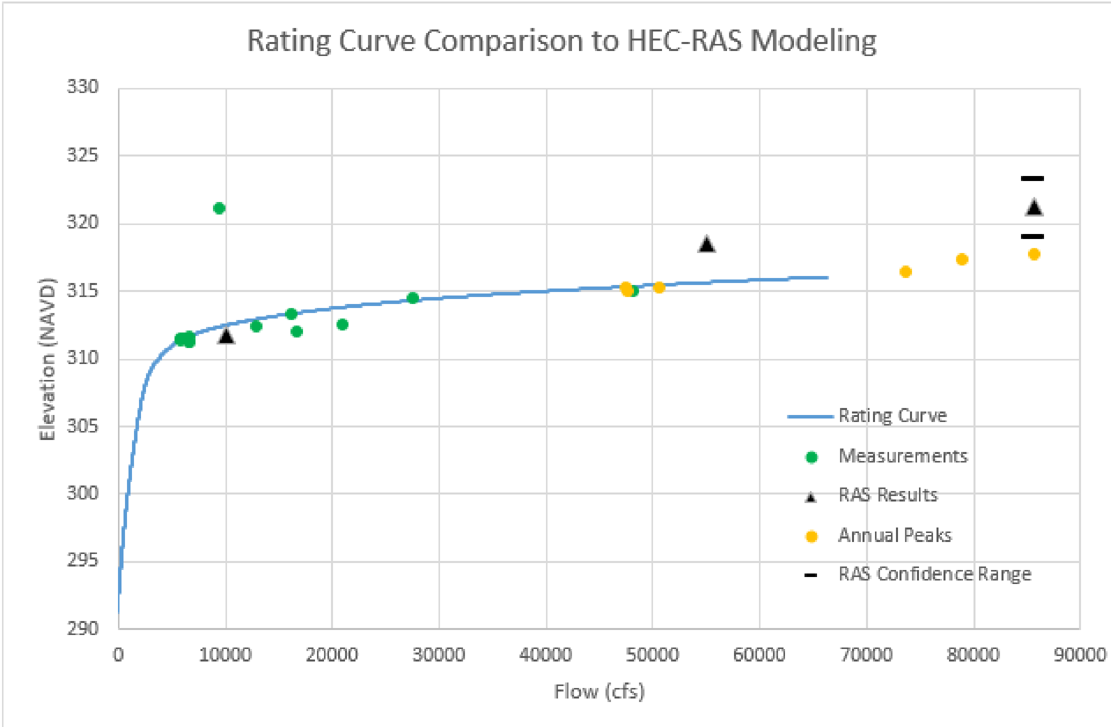


Figure 10.77: Rating Curve Comparison at Tehuacana Creek near Streetman Gage

Table 10.61: Comparison of Frequency Flows at Tehuacana Creek near Streetman Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				371,700		81,900		
0.004	200				224,500		66,200		
0.01	100				150,900		55,100		
0.02	50				99,600		43,700		
0.04	25				64,100		34,100		
0.1	10				34,000		20,400		
0.2	5				19,700		15,000		
0.5	2				7,900		7,100		

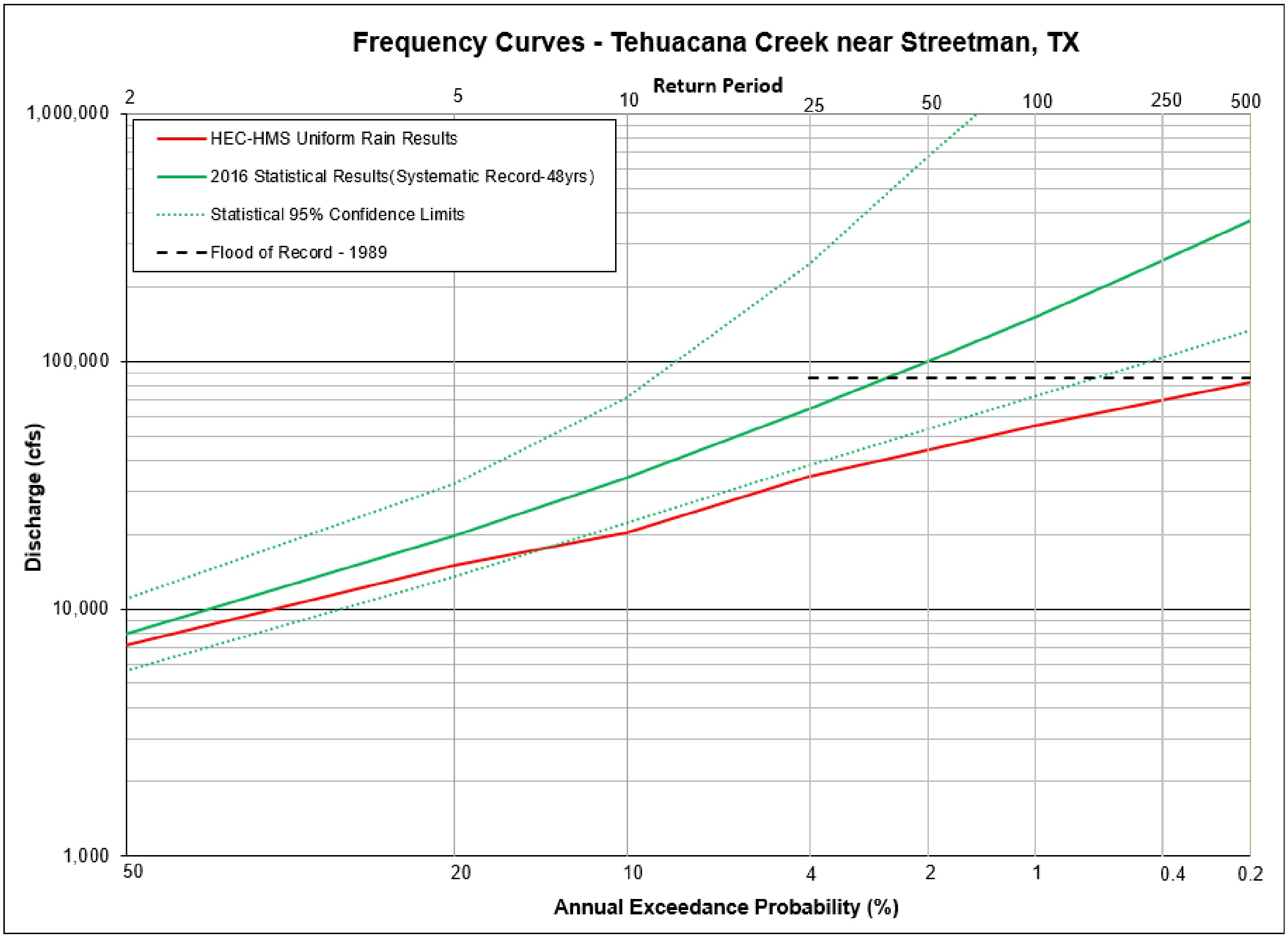


Figure 10.78: Flow Frequency Curve Comparison for Tehuacana Creek near Streetman Gage

Table 10.62: Comparison of Frequency Flows at Trinity River near Oakwood Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				167,300	187,200	438,500	308,900	
0.004	200				153,600	155,500	327,200	223,500	
0.01	100				141,500	133,000	261,200	152,400	
0.02	50				127,600	111,600	164,600	129,000	
0.04	25				111,900	85,200	126,100	107,400	
0.1	10				87,800	66,500	86,400	81,100	
0.2	5				66,800	48,800	62,700	59,500	
0.5	2				34,400	26,100	35,700	36,300	

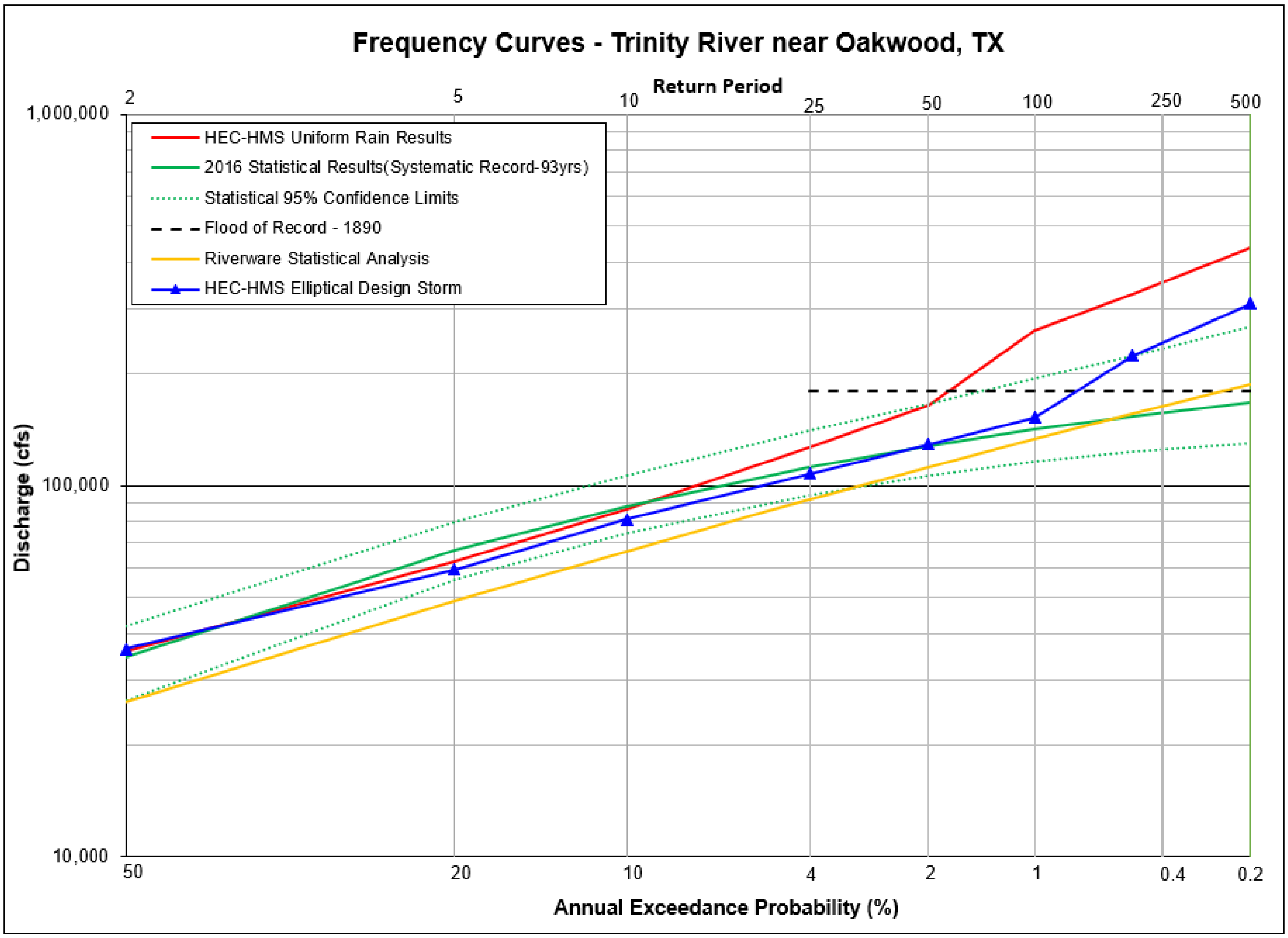


Figure 10.79: Flow Frequency Curve Comparison for Trinity River near Oakwood Gage

Figure 10.80 below provides a comparison between the 100-year calibrated rainfall-runoff model (HEC-HMS) results, observed annual peak flows, 100-year USGS regression equation results, and 100-year statistical hydrology results at the Trinity River near Oakwood USGS gage. The statistical hydrology results show how the 100-year statistical hydrology value has changed as each additional annual peak flow is added to the record. Generally, at least 300-400 years of record are needed before the 1% annual chance (100-yr) flow frequency estimates will stop significantly changing over time with additional years of record, unless additional information such as rainfall-runoff modeling estimates are utilized in the statistical analysis.

For this location, the HEC-HMS results have been both higher and lower than the statistical hydrology estimate as the statistical hydrology result has changed over time. The HEC-HMS results are well within the statistical hydrology 95% confidence limits and are higher than the statistical hydrology estimate using the full record length. The HEC-HMS results are higher than the USGS regression equation value, which considers the drainage area below USACE reservoirs and other major reservoirs.

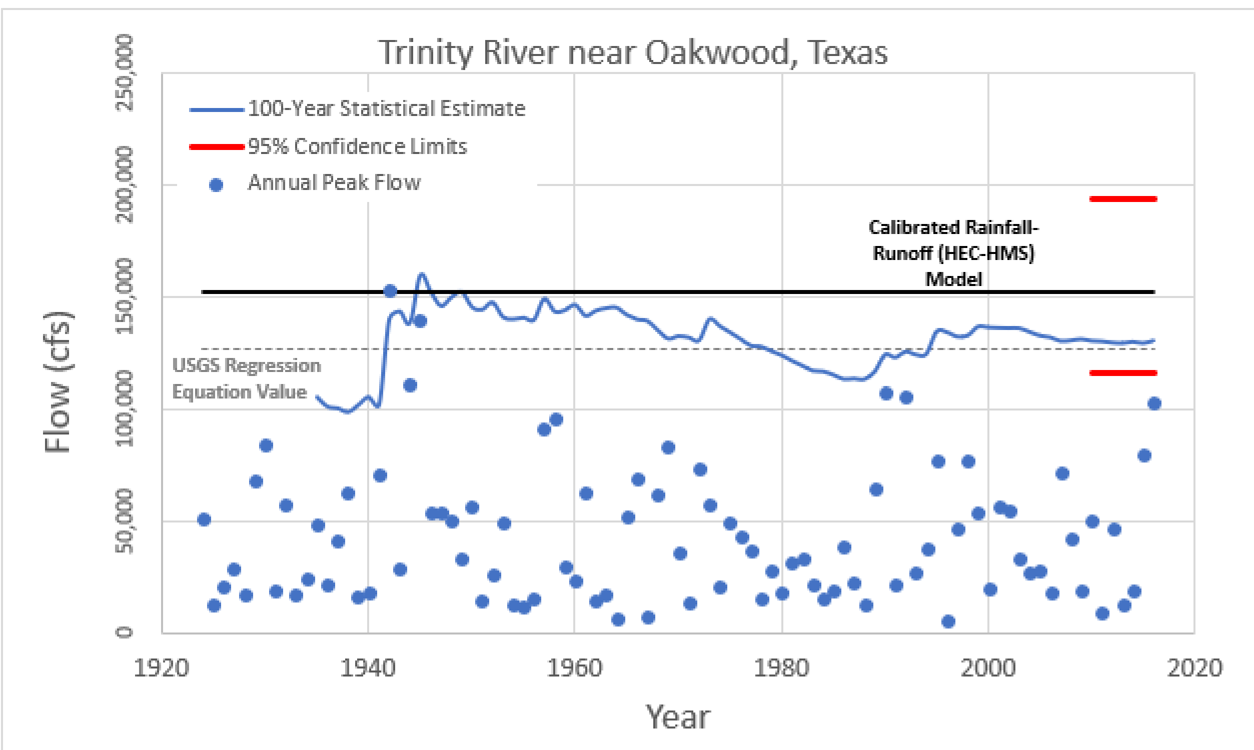


Figure 10.80 100-YR Flow Comparison for Trinity River near Oakwood Gage

Table 10.63: Comparison of Frequency Flows at Upper Keechi Creek near Oakwood Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				67,200		72,000		
0.004	200				51,800		58,300		
0.01	100				41,400		48,900		
0.02	50				32,100		39,200		
0.04	25				23,900		31,100		
0.1	10				14,800		19,500		
0.2	5				9,200		11,400		
0.5	2				3,400		3,400		

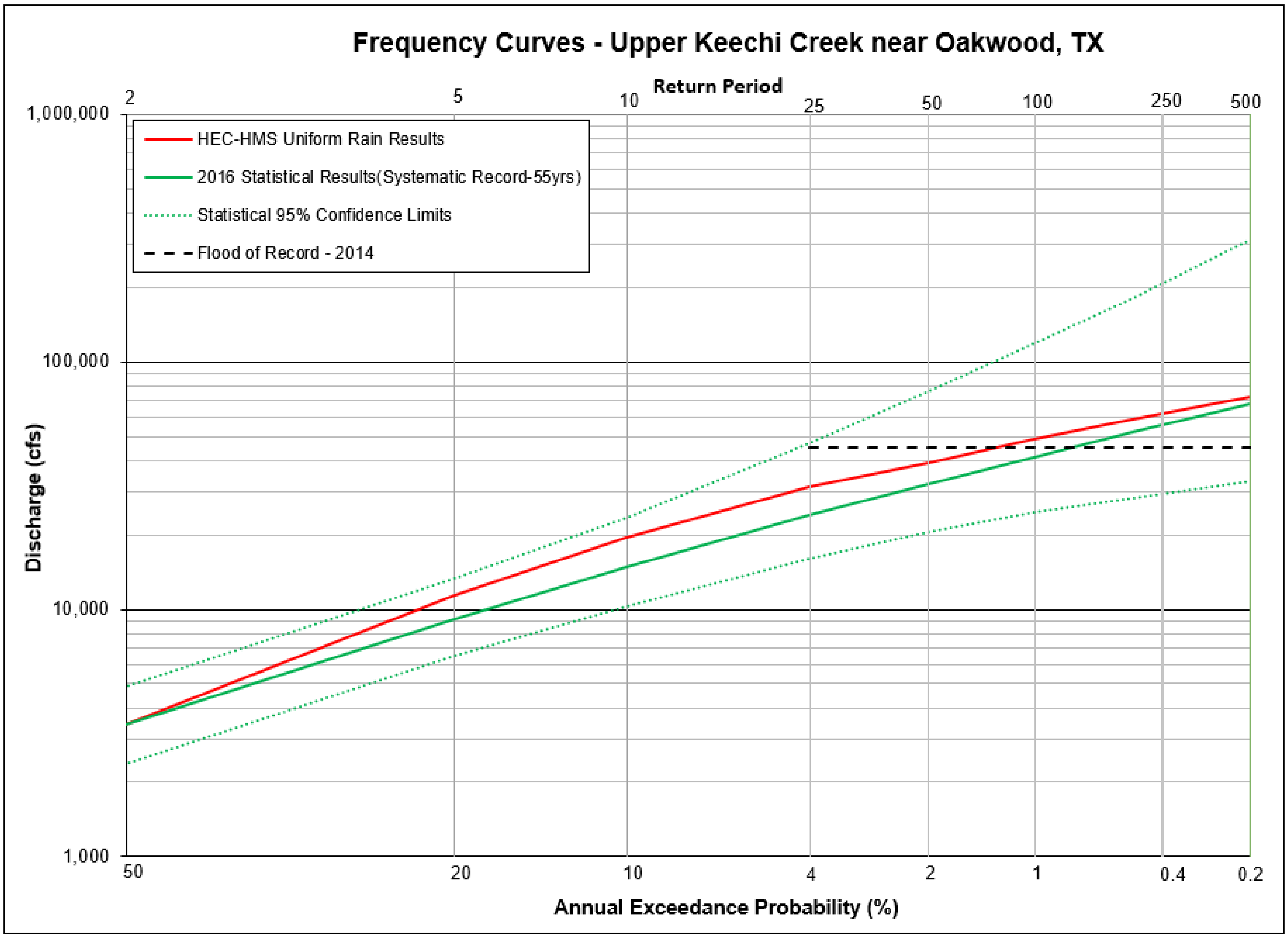


Figure 10.81: Flow Frequency Curve Comparison for Upper Keechi Creek near Oakwood Gage

Table 10.64: Comparison of Frequency Flows at Trinity River near Crockett Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				141,000	155,200	376,400	235,000	
0.004	200				126,400	133,600	281,500	160,600	
0.01	100				114,800	117,400	210,600	139,800	
0.02	50				102,600	101,200	157,800	121,900	
0.04	25				89,800	80,000	124,900	98,700	
0.1	10				71,800	64,100	81,900	71,500	
0.2	5				56,900	48,100	58,100	53,900	
0.5	2				34,400	26,300	34,000	33,300	

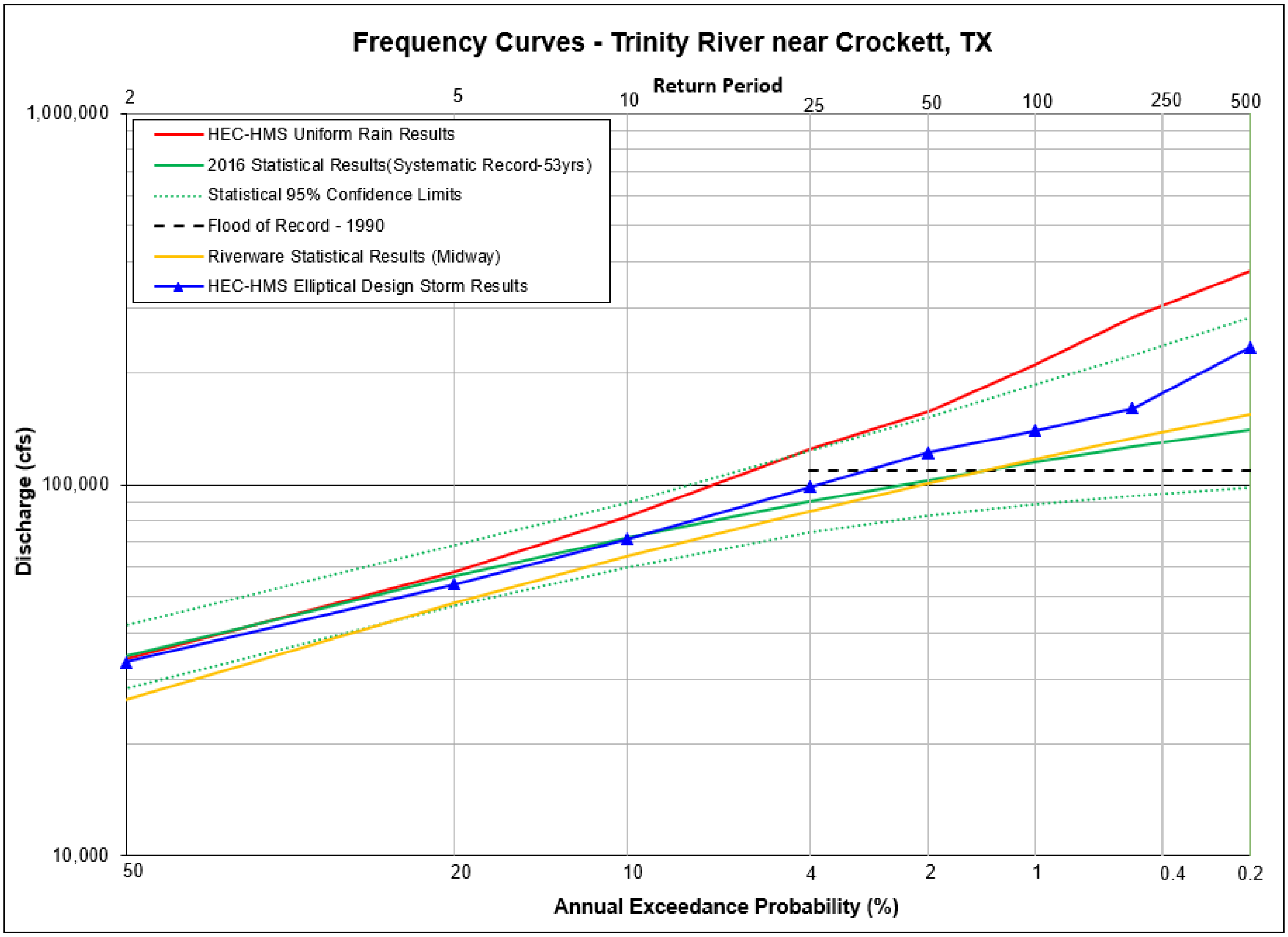


Figure 10.82: Flow Frequency Curve Comparison for Trinity River near Crockett Gage

Table 10.65: Comparison of Frequency Flows at Bedias Creek near Madisonville Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				82,900		105,800		
0.004	200				69,100		82,300		
0.01	100				58,900		65,100		
0.02	50				48,900		47,500		
0.04	25				39,400		38,000		
0.1	10				27,400		24,400		
0.2	5				18,900		16,200		
0.5	2				8,500		8,200		

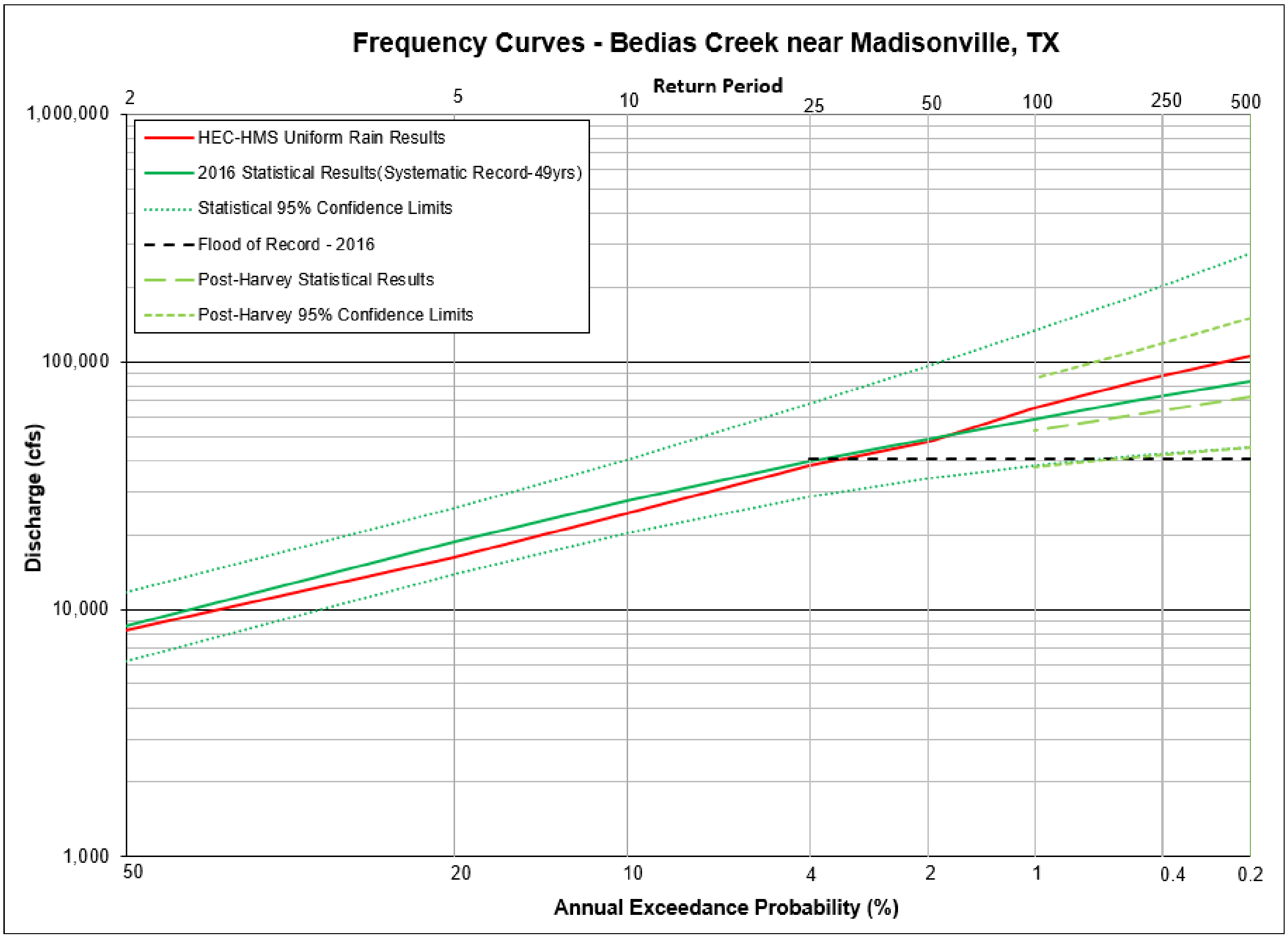


Figure 10.83: Flow Frequency Curve Comparison for Bedias Creek near Madisonville Gage

Table 10.66: Comparison of Frequency Flows at Trinity River at Riverside Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				180,400	139,000	341,000	249,200	
0.004	200				155,300	124,800	251,500	194,300	
0.01	100				136,800	113,500	202,600	158,700	
0.02	50				118,600	101,500	157,500	133,800	
0.04	25				100,700	84,600	128,400	109,300	
0.1	10				77,400	70,800	81,400	71,800	
0.2	5				59,800	55,900	63,500	61,500	
0.5	2				35,300	33,400	34,000	41,000	

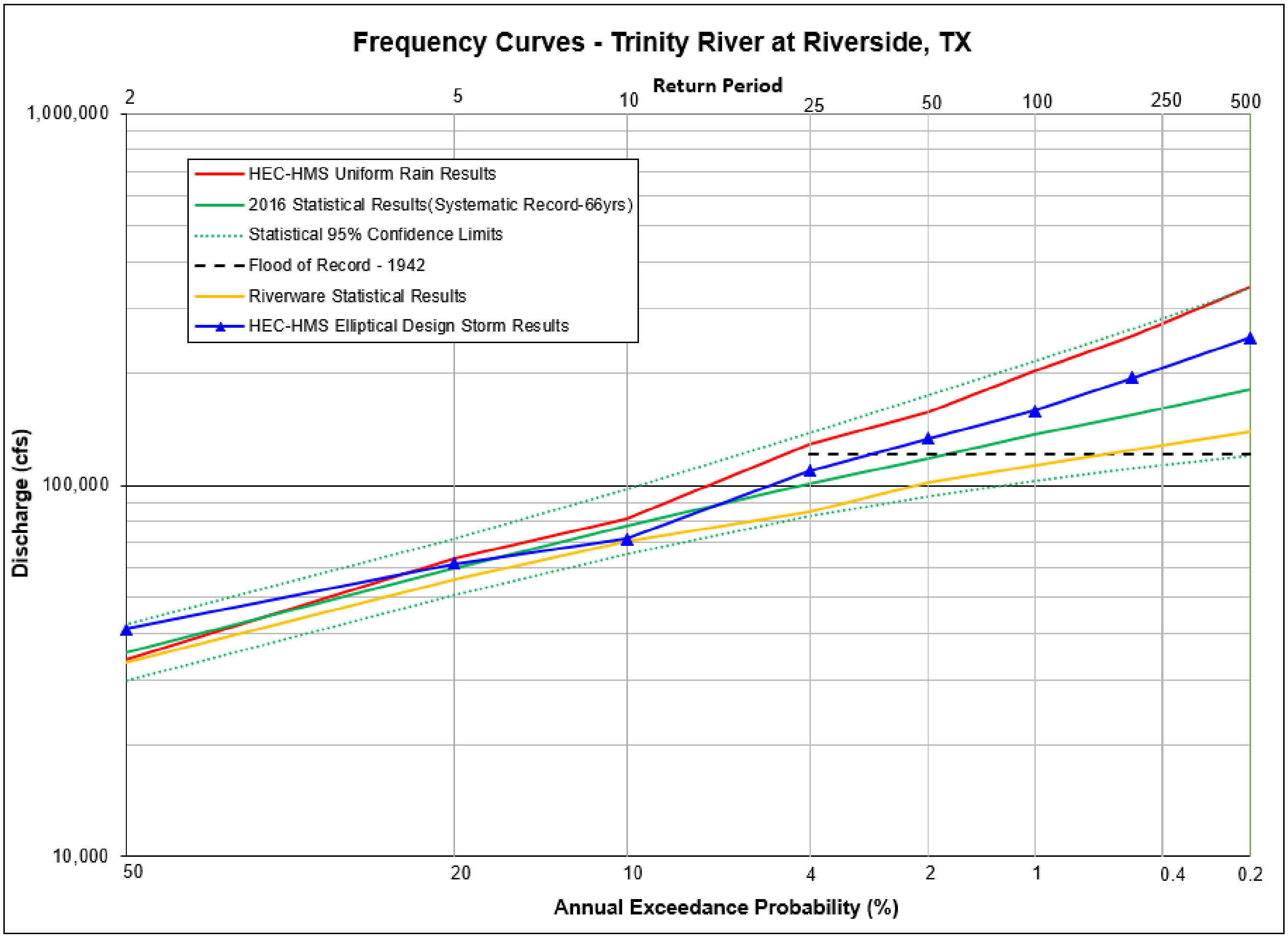


Figure 10.84: Flow Frequency Curve Comparison for Trinity River at Riverside Gage

Table 10.67: Comparison of Frequency Flows at Kickapoo Creek near Onalaska Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				91,200				
0.004	200				65,700				
0.01	100				50,500				
0.02	50				38,000				
0.04	25				27,900				
0.1	10				17,500				
0.2	5				11,500				
0.5	2				5,300				

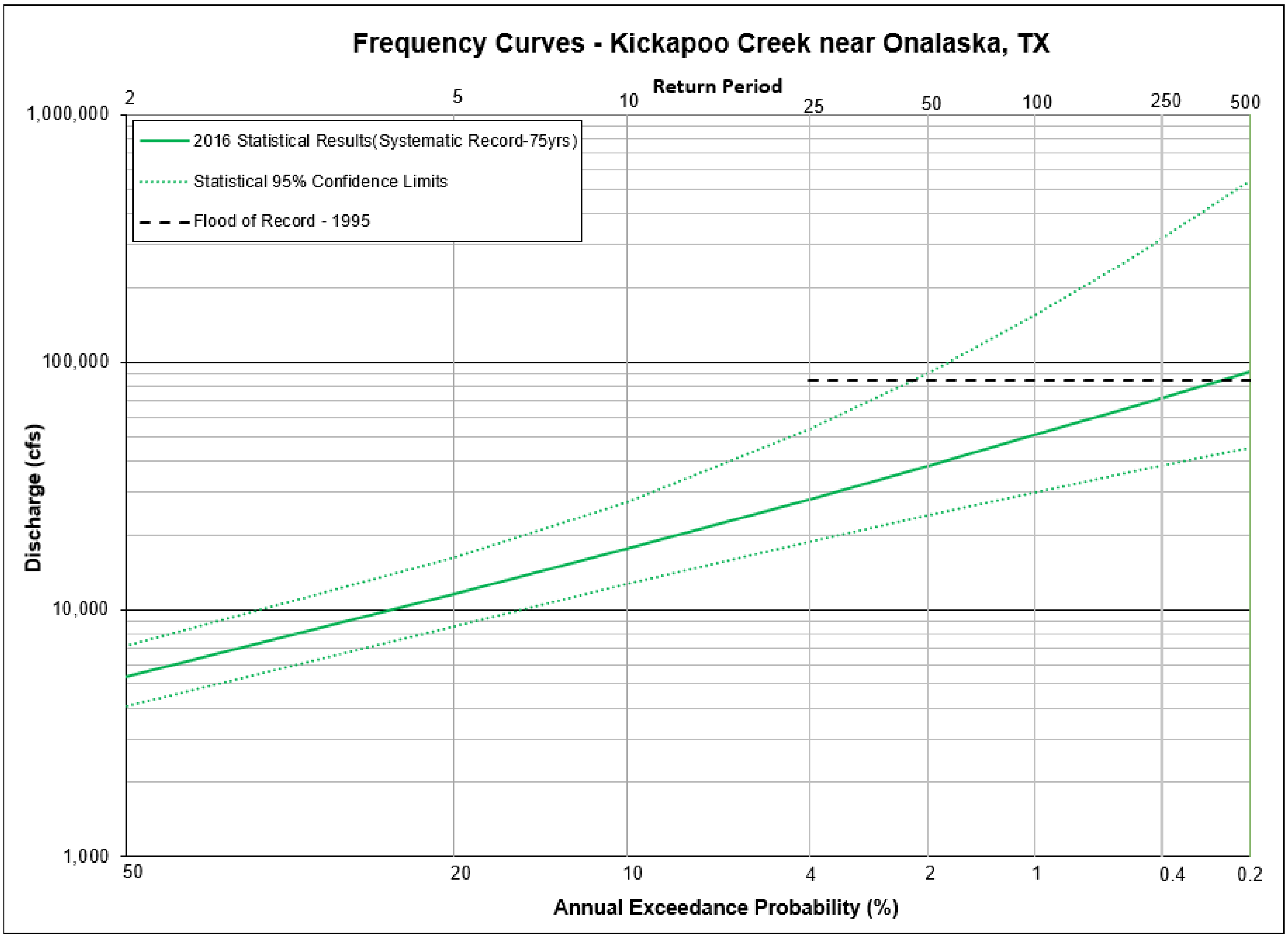


Figure 10.85: Flow Frequency Curve Comparison for Kickapoo Creek near Onalaska Gage

Table 10.68: Comparison of Frequency Flows at Long King Creek at Livinston Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				72,700		69,400		
0.004	200				56,700		55,800		
0.01	100				46,100		46,300		
0.02	50				36,800		36,500		
0.04	25				28,600		28,700		
0.1	10				19,300		19,700		
0.2	5				13,300		13,600		
0.5	2				6,500		5,700		

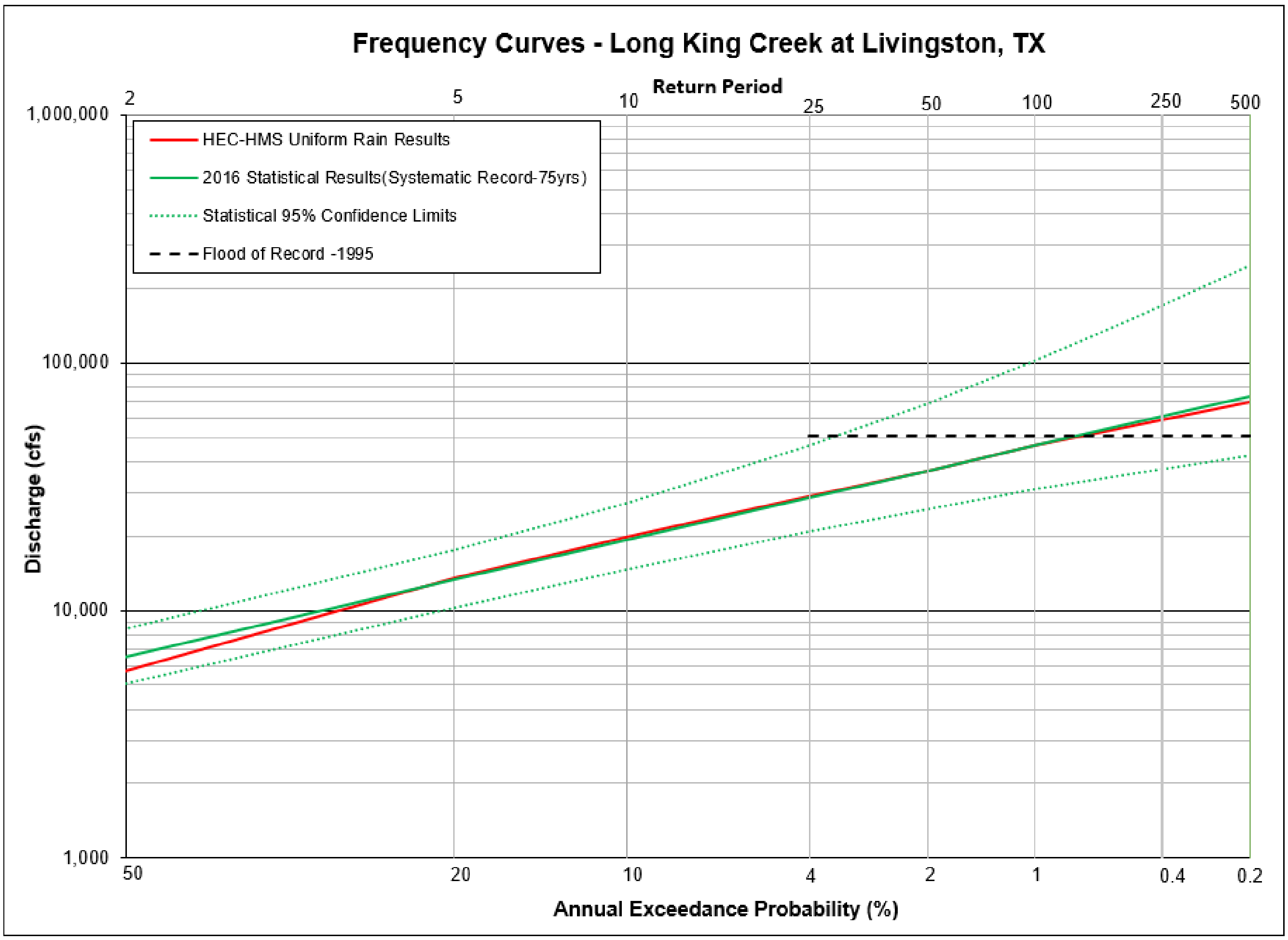


Figure 10.86: Flow Frequency Curve Comparison for Long King Creek at LIvingston Gage

Table 10.69: Comparison of Frequency Flows at Trinity River near Goodrich Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				142,800		416,000	282,700	
0.004	200				131,100		315,500	211,200	
0.01	100				121,600		245,800	162,200	
0.02	50				111,400		176,300	126,400	
0.04	25				100,400		129,300	104,700	
0.1	10				84,300		96,500	84,400	
0.2	5				70,400		75,700	69,000	
0.5	2				47,700		36,100	40,000	

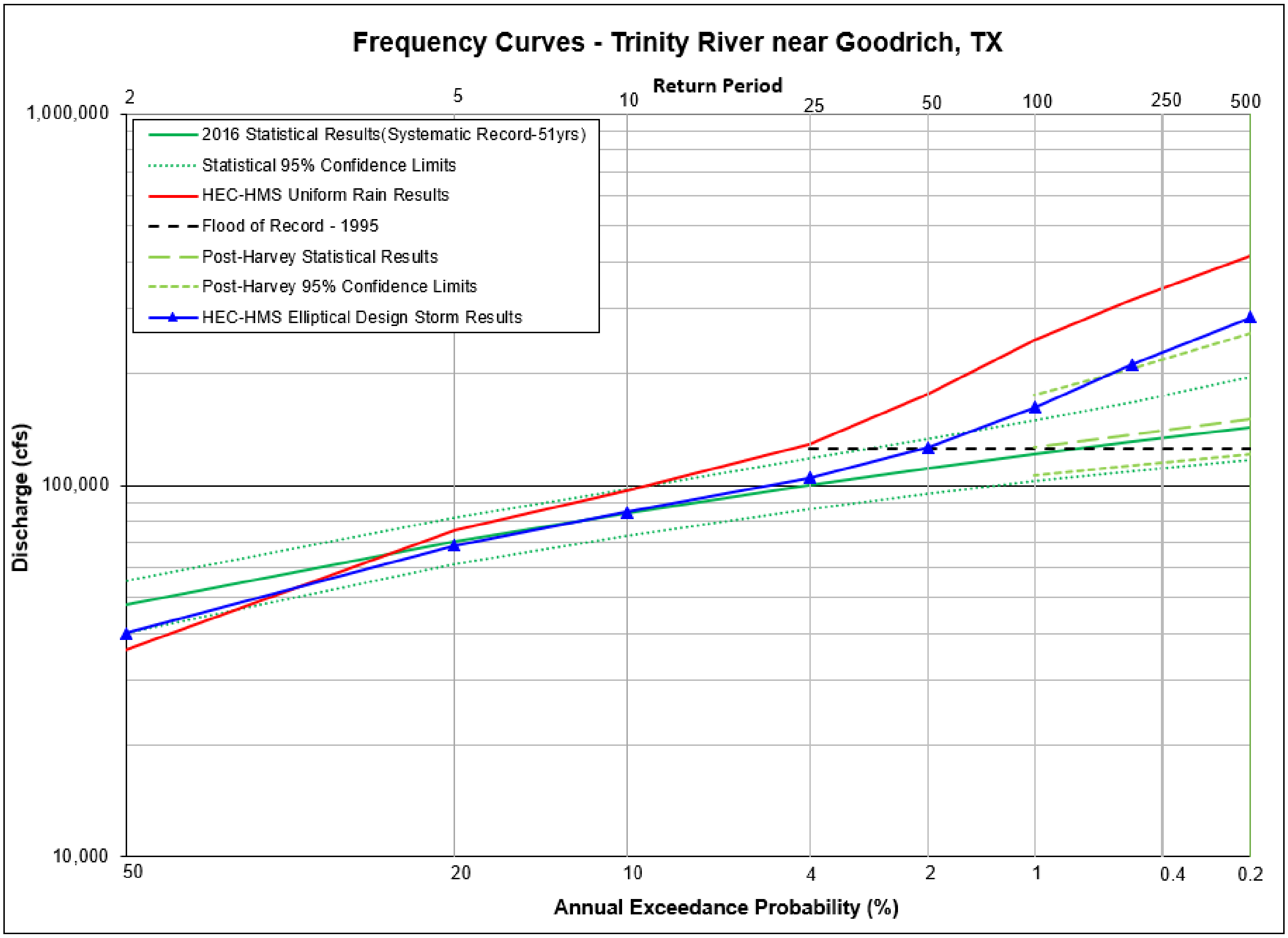


Figure 10.87: Flow Frequency Curve Comparison for Trinity River near Goodrich Gage

Table 10.70: Comparison of Frequency Flows at Mendard Creek near Rye Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	37,400			29,000		44,400		
0.004	200				23,500		34,700		
0.01	100	26,300			19,600		27,900		
0.02	50	21,500			15,900		20,800		
0.04	25				12,500		15,600		
0.1	10	11,600			8,400		10,000		
0.2	5				5,600		6,300		
0.5	2				2,400		2,300		

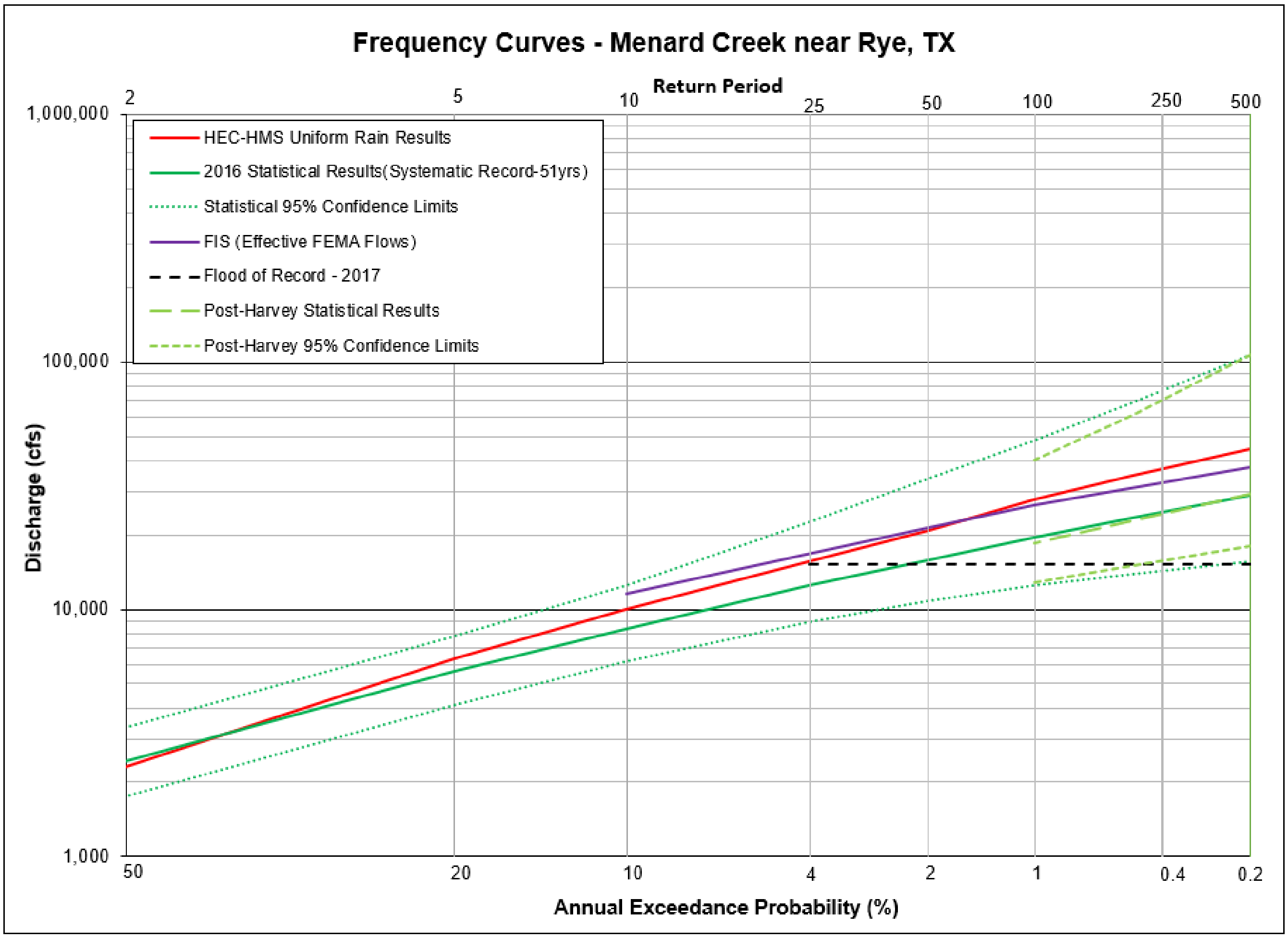


Figure 10.88: Flow Frequency Curve Comparison for Menard Creek near Rye Gage

Table 10.71: Comparison of Frequency Flows at Trinity River at Romayor Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500				130,500	112,500	338,400	218,100	
0.004	200				122,700	100,200	245,100	157,100	
0.01	100				115,800	91,100	185,000	126,200	
0.02	50				107,700	82,000	136,900	107,000	
0.04	25				98,300	70,200	108,000	93,100	
0.1	10				83,200	61,100	85,700	76,500	
0.2	5				69,000	51,600	69,200	62,900	
0.5	2				44,200	37,500	37,500	40,700	

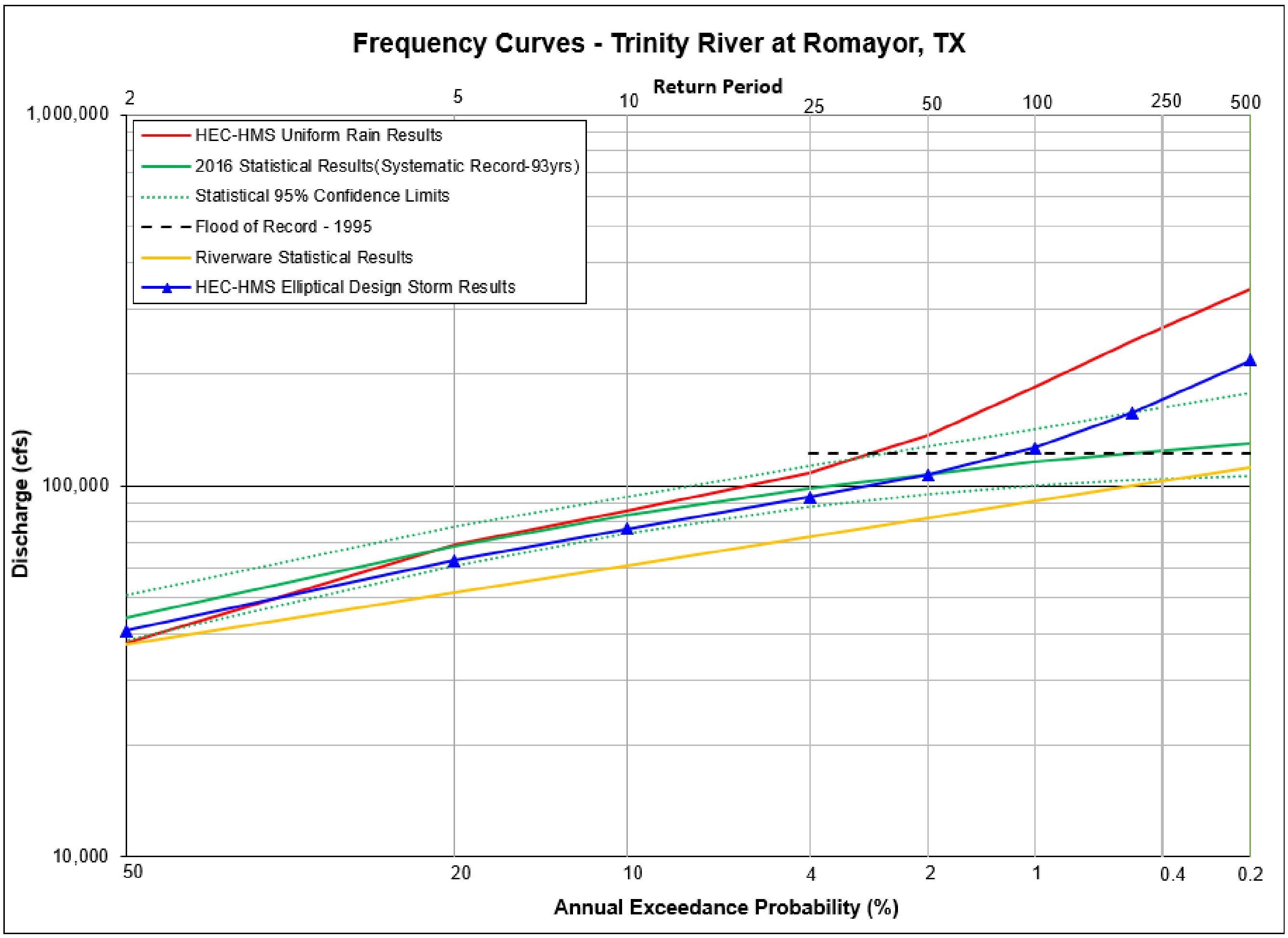


Figure 10.89: Flow Frequency Curve Comparison for Trinity River at Romayor Gage

Figure 10.90 below provides a comparison between the 100-year calibrated rainfall-runoff model (HEC-HMS) results, observed annual peak flows, 100-year USGS regression equation results, and 100-year statistical hydrology results at the Trinity River at Romayor USGS gage. The statistical hydrology results show how the 100-year statistical hydrology value has changed as each additional annual peak flow is added to the record. Generally, at least 300-400 years of record are needed before the 1% annual chance (100-yr) flow frequency estimates will stop significantly changing over time with additional years of record, unless additional information such as rainfall-runoff modeling estimates are utilized in the statistical analysis.

For this location, the HEC-HMS results have been both higher and lower than the statistical hydrology estimate as the statistical hydrology result has changed over time. The HEC-HMS results are well within the statistical hydrology 95% confidence limits and are similar to the statistical hydrology estimate using the full record length. The HEC-HMS results are lower than the USGS regression equation value, which considers the drainage area below USACE reservoirs and other major reservoirs.

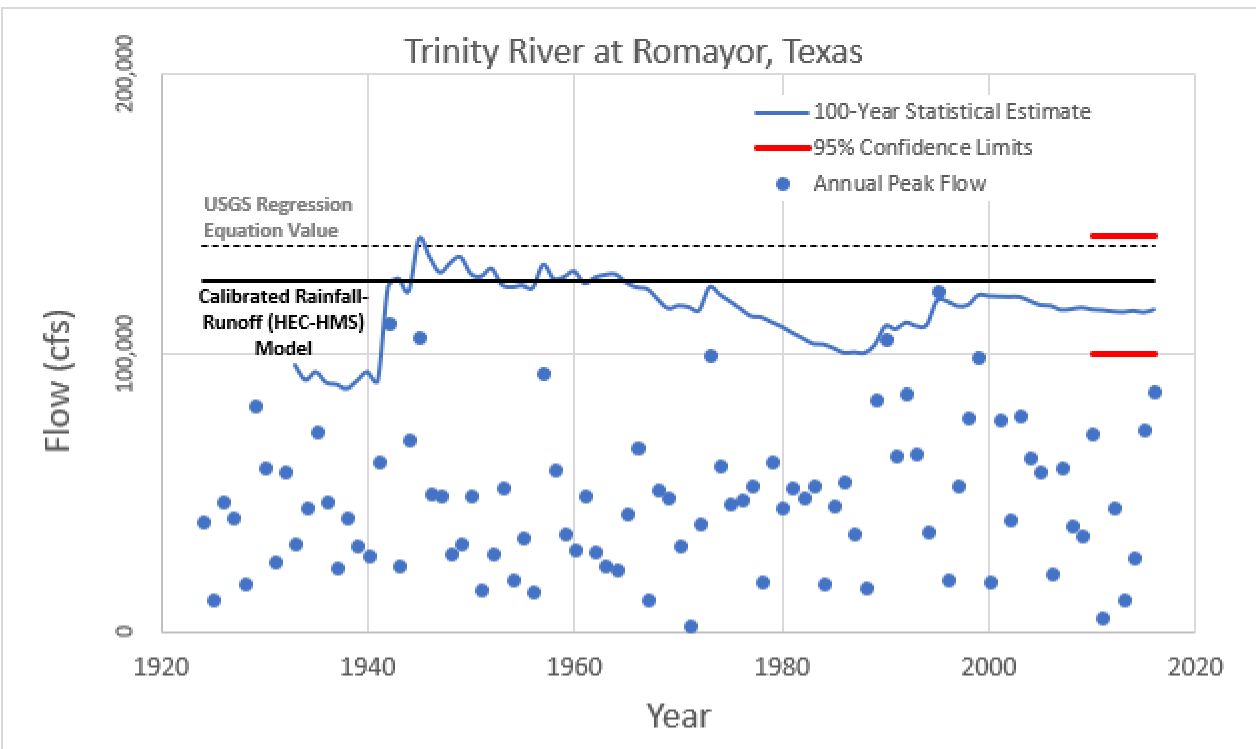


Figure 10.90 100-YR Flow Comparison for Trinity River at Romayor Gage

Table 10.72: Comparison of Frequency Flows at Trinity River at Liberty Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	235,000			140,600		338,600	205,300	
0.004	200				129,200		245,500	151,100	
0.01	100	127,000			119,700		185,200	120,900	
0.02	50	110,000			109,300		136,500	103,700	
0.04	25				97,900		106,300	90,200	
0.1	10	72,000			80,900		84,100	70,800	
0.2	5				66,000		66,000	54,500	
0.5	2				41,800		33,000	34,800	

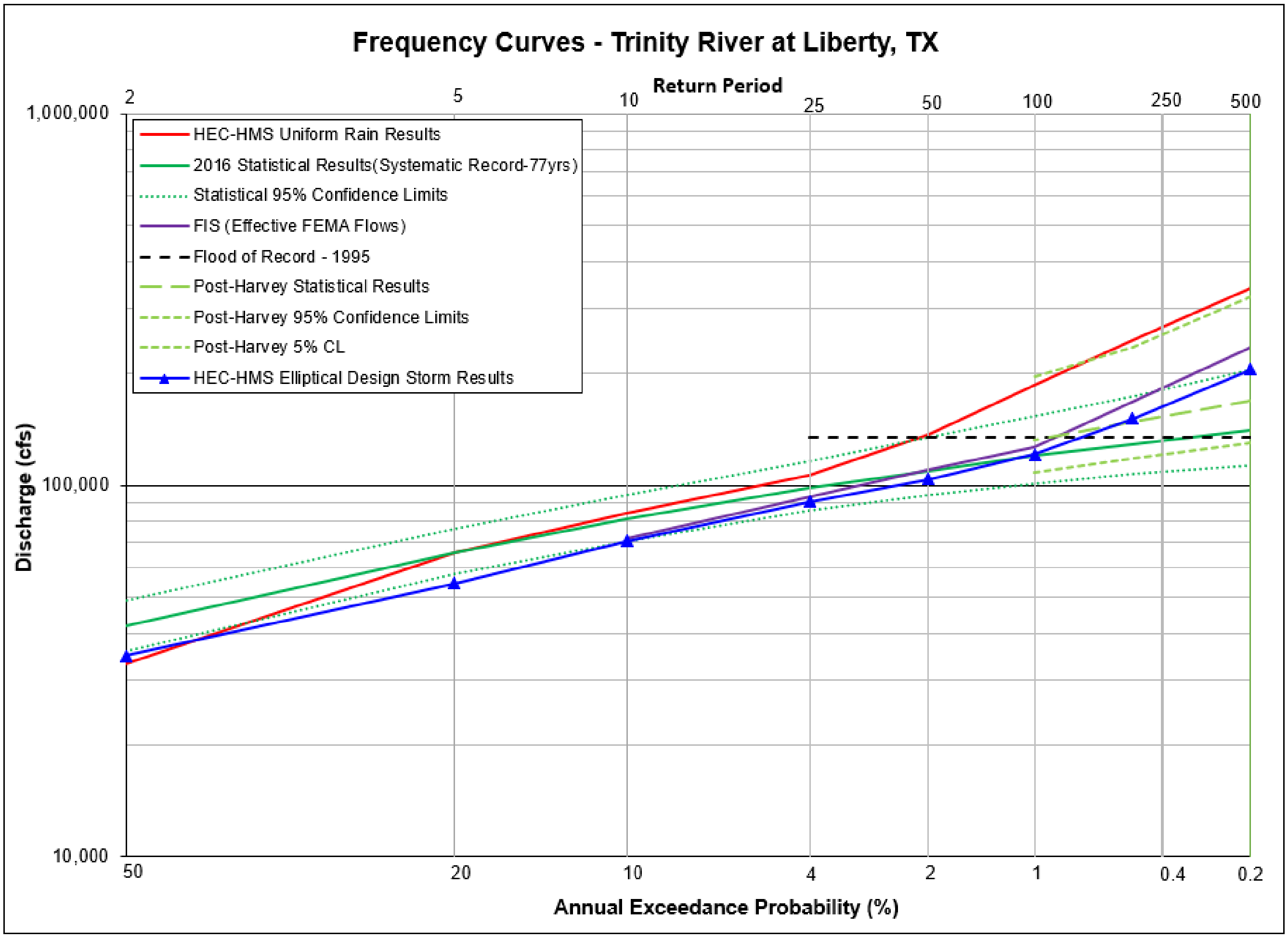


Figure 10.91: Flow Frequency Curve Comparison for Trinity River at Liberty Gage

Table 10.73: Comparison of Frequency Flows at Trinity River at Wallisville Gage

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS	Preliminary FEMA FIS (RAMPP team)	Previous USACE Study	Statistical Analysis of USGS data	Riverware POR Statistical Analysis	HEC-HMS Model Uniform Rain with NOAA Atlas 14 (cfs)	HEC-HMS Model Elliptical Storm with NOAA Atlas 14 (cfs)	Reservoir Analysis
0.002	500	265,000					339,700	188,300	
0.004	200						246,400	141,800	
0.01	100	127,000					185,700	115,300	
0.02	50	110,000					135,000	98,700	
0.04	25						104,800	84,000	
0.1	10	72,000					80,900	62,400	
0.2	5						61,800	45,700	
0.5	2						32,300	32,300	

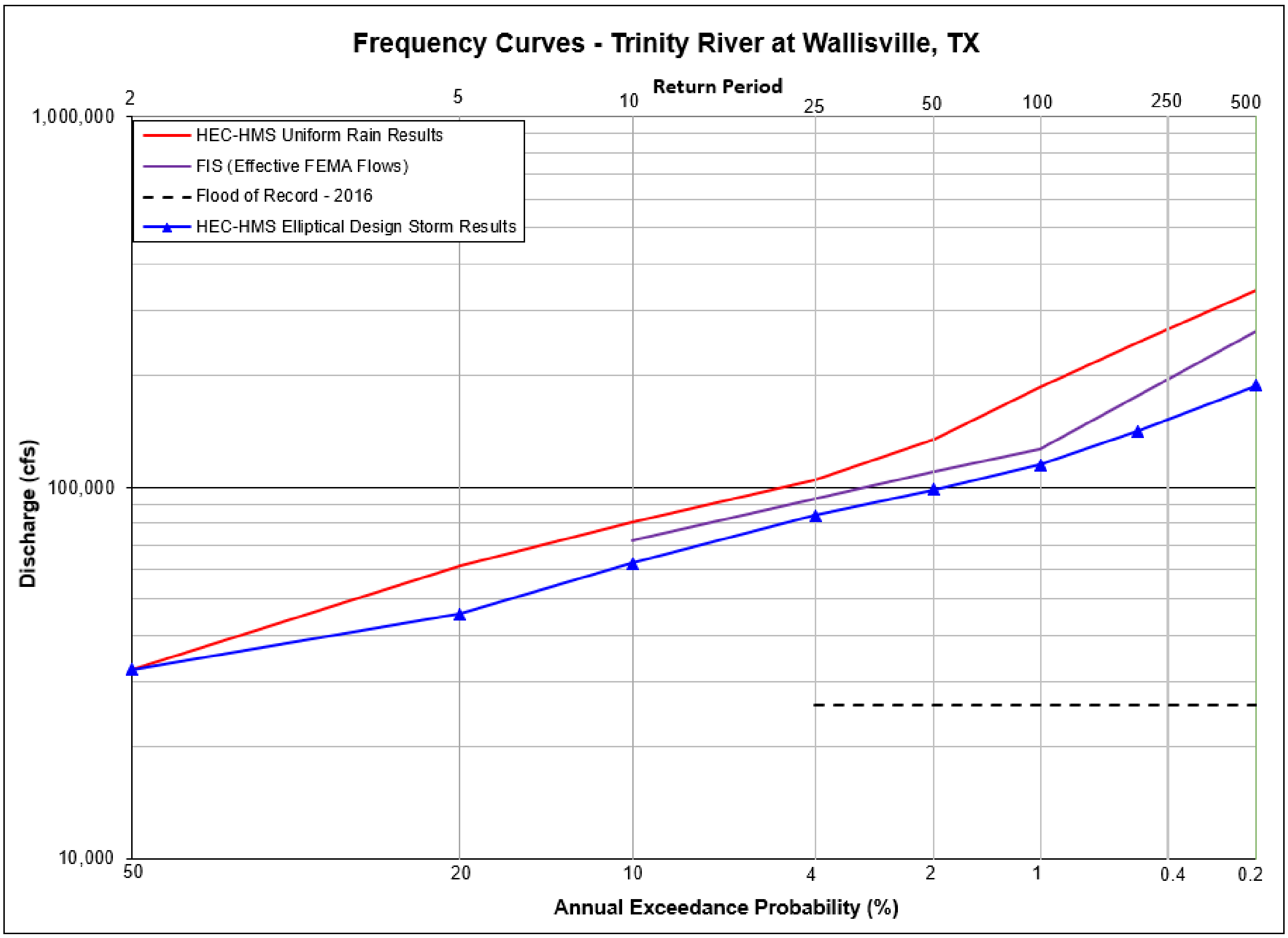


Figure 10.92: Flow Frequency Curve Comparison for Trinity River at Wallisville Gage

11 Frequency Flow and Pool Elevation Recommendations

The final recommendations for the InFRM Watershed Hydrology Assessments are formulated through a rigorous process which requires technical feedback and collaboration between all of the InFRM subject matter experts. This process includes the following steps at a minimum: (1) comparing the results of the various hydrologic methods to one another, (2) performing an investigation into the reasons for the differences in results at each location in the watershed, (3) selecting of the draft recommended methods, (4) performing interal and external technical reviews of the hydrologic analyses and the draft recommendations, and finally, (5) finalizing the study recommendations.

After completing this process for the Trinity River basin, the frequency discharges that were recommended for adoption by the InFRM team were a combination of the results from the following methods: HEC-HMS NOAA Atlas 14 uniform rain, HEC-HMS NOAA Atlas 14 Elliptical Storms, and Reservoir Studies. A detailed breakout of the recommended discharges and pool elevations for each node in the watershed is given in Table 11.1 and Table 11.2.

The statistical results from Chapter 5 and the Riverware statistical results from Chapter 8 were used as a point of comparison, especially at the frequent end of the curves, but the InFRM team chose not to adopt the statistical flow frequency results directly. One reason for this decision was the tendency of the statistical results to change after each significant flood event, as demonstrated in the change over time plots in Section 5.3. In addition, climate variability from wet to dry may result in non-representative samples in the gage record. Rainfall runoff modeling, on the other hand, is based on physical watershed characteristics, such as drainage area and stream slope, that do not tend to change as much over time. Climate variability can also be accounted for in the watershed model by adjusting soil loss rates to be consistent with observed storms and appropriate for the rarity of the event in question. Another reason for the selection of the HEC-HMS modeling discharges was the ability to directly calculate frequency discharges for other locations within the Trinity River watershed that do not coincide with a stream gage. The statistical frequency analyses and Riverware results support the HEC-HMS modeling results by demonstrating that they are generally within the confidence limits, especially for the 1% and 0.2% AEP events of interest for FEMA floodplain mapping.

Rainfall-runoff modeling in HEC-HMS was used to simulate the physical processes that occur in the watershed during storm events, such as the movement of water across the land surface and through the streams and rivers. The HEC-HMS model for the Trinity River basin underwent extensive calibration to accurately simulate the response of the watershed to a range of observed flood events, including large events similar to a 1% ACE (100-yr) flood. In fact, a total of seventeen recent storm events were used to fine tune the HEC-HMS model; thereby bestowing a high degree of confidence in the HEC-HMS model's results. Rainfall-runoff modeling is also a more direct method of accounting for changes in land use, which is a major issue in the upper Trinity watershed due to the expanding Dallas-Fort Worth metroplex.

In addition to extensive calibration of the parameters simulating watershed response, best available precipitation frequency estimates (NOAA, 2018) were used within the HEC-HMS models. There are a couple factors that make NOAA Atlas 14 the most accurate, up-to-date, and comprehensive study of rainfall depths in Texas. First, the NOAA Atlas 14 study contained an additional 23 years of rainfall data compared to the previous precipitation product developed by the USGS in 2004, which only included data through 1994. Some of the largest storms on record in the Trinity River basin have occurred within the last 23 years, and the 2004 USGS rainfall study did not include any data from those recent large Trinity flood events, most notably Hurricane Harvey in 2017 on the lower end of the Trinity. Secondly, NOAA Atlas 14 used a regional statistical approach that incorporated at least 1,000 cumulative years of daily data and 500 cumulative years of sub-daily data into each station's rainfall frequency estimate. This regional approach yielded better estimates of rare rainfall depths such as the 1% and 0.2% AEP (100-yr and 500-yr) depths. For these reasons, the calibrated HEC-HMS watershed modeling with the NOAA Atlas 14 rainfall depths was adopted as having the most complete accounting of both the historic rainfall data and the physical processes at work in the watershed.

Between the uniform rain and the elliptical storm HEC-HMS results presented in Chapter 8, the uniform rain method is simpler and well suited for smaller drainage areas, while the elliptical storm method is more complex and better suited for larger drainage areas. As discussed in Section 7.7, the results from the uniform rainfall method in HEC-HMS generally appeared to be reasonable up to at least 1,000 square miles. For larger drainage areas in the Trinity River basin, which ranged from 1,000 to 13,600 square miles, the elliptical storm results from HEC-HMS did a better job of producing reasonable runoff volumes and subsequently peak streamflows. Table 11.2 indicates where results transitioned from uniform rainfall results to elliptical storm results. The exact locations of the transitions between uniform and elliptical storms generally occurred at locations with drainage areas between 400 and 1,000 square miles and were placed at significant confluences to avoid any small jumps or dips in the peak flows due to a change in the rainfall method.

For the reaches downstream USACE dams, there are two distinct sources of flooding: (1) a large release from the dam and (2) local rainfall runoff from the drainage area downstream of the dam. For the first flooding source, the frequency of releases were calculated in the reservoir study in Chapter 9. The reservoir study was performed for the 8 USACE reservoirs within the basin as well as Richland-Chambers reservoir. These studies took the most detailed and comprehensive look at the operations of the dam, the frequency and volumes of the inflow hydrographs, and expected frequency of its pool elevations. The resulting recommended frequency pool elevations are shown in Table 11.1. This table also contains recommended frequency pool elevations using methods less comprehensive than the reservoir study method.. While these results do represent a picture of flood risk using best available scientific modeling and information, they are unable to fully account for all the variables such as starting pool elevation, variances in reservoir operation, and inflow hydrograph shape and duration variation that make up the true or actual frequency pool elevations for a reservoir, which are better accounted for in the reservoir study methodology presented in Chapter 9. These less comprehensive methods can be used as a starting point for pool frequency information where there is no existing information or where information is less detailed. It is recommended that more detailed and comprehensive analysis be performed, such as in the reservoir study methods applied within this study, if possible. The corresponding frequency outflows from the Resevoir Study as well as frequency flows for the rest of the watershed are in Table 11.1. For the second flooding source, peak flows from the local rainfall runoff were calculated in the HEC-HMS model with the NOAA Atlas 14 rainfall in Chapter 6. The frequency peak flows from these two flooding sources were then compared to one another for each reach of the river, and the higher of the two peak flows were recommended for adoption. In general, the results showed that releases from USACE dams dominate the Trinity River discharges immediately downstream of the dam, and then as one continues downstream, the flows from the local rainfall runoff increase and eventually become dominant.

Table 11.1: Recommended Frequency Pool Elevationa (ft-NAVD) (Stillwater Elevations at Dam)

Reservoir	Drainage Area*	50%	20%	10%	4%	2%	1%	0.50%	0.20%	Hydrologic Method
	sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR	
Lost Creek Reservoir	28.8	1011.4	1014.3	1015.9	1016.8	1017.2	1017.6	1017.9	1018.2	Uniform HEC-HMS
Bridgeport Reservoir	1095.7	836.1	837.1	839.5	842.2	845.5	848.8	851.4	855.6	Elliptical HEC-HMS
Amon G Carter Lake	109.5	921.4	923.2	925.0	927.2	928.7	930.1	931.3	933.0	Uniform HEC-HMS
Eagle Mountain Reservoir	1956.6	649.2	650.1	651.3	654.0	656.5	659.5	662.2	666.0	Elliptical HEC-HMS
Lake Worth	2050.8	595.2	596.2	597.3	597.7	598.6	599.5	600.2	601.2	Elliptical HEC-HMS
Lake Weatherford	108.7	897.6	898.9	900.8	904.5	905.9	907.0	907.7	908.8	Uniform HEC-HMS
Benbrook Lake	429.2	697.2	704.0	711.0	713.7	715.7	717.6	720.3	722.3	Reservoir Study
Marine Creek Reservoir	9.1	690.3	692.2	693.5	695.3	696.7	698.4	700.0	702.1	Uniform HEC-HMS
Lake Arlington	143.1	553.1	555.5	557.8	560.8	562.5	564.0	565.2	566.3	Uniform HEC-HMS
Joe Pool Lake	224.2	524.5	527.0	531.0	535.3	537.5	539.0	540.8	542.2	Reservoir Study
Mountain Creek Lake	70.6	458.4	458.7	459.0	459.2	459.3	459.5	459.7	459.9	Uniform HEC-HMS
Muenster Lake	14	1025.0	1026.8	1029.0	1032.7	1035.8	1038.6	1039.3	1039.9	Uniform HEC-HMS
Lake Kiowa	16.8	701.2	702.4	703.2	704.2	704.9	705.6	706.3	707.2	Uniform HEC-HMS
Ray Roberts Lake	692.6	633.3	635.7	639.5	641.1	644.0	645.5	647.2	648.5	Reservoir Study
SCS Dam 49	24.7	743.4	746.3	748.0	749.8	751.0	752.3	753.1	753.5	Uniform HEC-HMS
Lewisville Lake	968.2	523.9	527.8	532.2	535.0	536.5	537.8	539.3	540.5	Reservoir Study
Grapevine Lake	694.4	538.1	546.1	556.1	561.6	562.9	564.1	565.7	567.0	Reservoir Study
Bachman Lake	12.7	441.1	442.7	443.6	444.4	444.8	445.1	445.4	445.6	Uniform HEC-HMS
White Rock Lake	95	461.5	462.6	463.5	464.6	465.4	466.3	467.1	468.2	Uniform HEC-HMS
Lake Lavon	768.2	493.9	499.5	502.8	503.7	504.0	504.3	504.7	505.0	Reservoir Study
Ray Hubbard Lake	301.8	436.1	436.5	436.8	437.2	437.5	437.9	438.1	438.4	Uniform HEC-HMS
New Terrell City Lake	14	505.4	506.4	507.1	508.4	509.4	510.0	510.2	511.0	Uniform HEC-HMS
Cedar Creek Reservoir	1010.8	322.4	322.8	323.1	323.4	323.7	323.9	324.5	325.6	Elliptical HEC-HMS
Lake Waxahachie	30.6	533.0	534.1	535.0	536.1	536.7	537.5	538.3	538.7	Uniform HEC-HMS
Bardwell Lake	174.4	425.7	430.9	434.5	438.1	440.0	441.5	443.2	444.2	Reservoir Study
Lake Halbert	11.5	369.0	369.7	370.2	370.8	371.3	371.8	372.3	372.9	Uniform HEC-HMS
Navarro Mills Lake	319.9	431.0	436.2	439.9	443.3	444.1	444.6	445.3	445.8	Reservoir Study
Richland Chambers Reservoir	1465.5	315.9	316.3	316.6	317.1	317.4	317.6	318.0	318.3	Reservoir Study
Fairfield Lake	36.2	310.3	310.4	310.5	310.9	311.3	311.9	312.4	313.2	Uniform HEC-HMS
Houston County Lake	48	260.9	261.4	262.2	263.6	265.1	266.4	267.5	268.7	Uniform HEC-HMS
Lake Livingston	12301.1	132.3	132.7	133.1	133.7	134.4	135.0	135.7	136.5	Elliptical HEC-HMS

*Drainage area is uncontrolled area downstream of USACE dams.

Table 11.2: Summary of Recommended Frequency Flows for the Trinity River Basin

Location Description	Drainage Area*	50%	20%	10%	4%	2%	1%	0.50%	0.20%	Hydrologic Method
	sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR	
West Fork Trinity River below Brushy Creek	191.1	3,600	10,200	16,700	24,700	31,400	39,500	46,900	57,300	Uniform HEC-HMS
West Fork Trinity River at Hwy 281 (TRWB's Antelope Gage)	231.5	3,200	10,200	17,900	27,900	36,500	46,900	56,300	69,000	Uniform HEC-HMS
West Fork Trinity River above Cameron Creek	263.3	1,600	5,600	11,200	19,600	28,100	40,100	51,300	66,200	Uniform HEC-HMS
West Fork Trinity River below Cameron Creek	332.4	3,600	8,800	14,000	25,400	37,100	53,300	68,100	87,700	Uniform HEC-HMS
West Fork Trinity River above Turkey Creek	403.1	2,300	7,600	14,200	25,200	36,800	53,600	69,200	91,700	Uniform HEC-HMS
West Fork Trinity River below Turkey Creek	439.2	2,600	8,100	15,000	26,500	39,000	57,200	73,900	98,300	Uniform HEC-HMS
West Fork Trinity River above Big Cleveland Creek	549.4	2,100	6,400	11,800	20,800	30,900	47,400	63,100	86,400	Uniform HEC-HMS
West Fork Trinity River below Big Cleveland Creek	648.1	3,600	7,100	12,400	21,200	32,000	50,700	68,400	95,400	Uniform HEC-HMS
West Fork Trinity River near Jacksboro, TX USGS gage	668.7	2,100	6,100	11,400	20,300	30,600	48,200	65,100	91,500	Uniform HEC-HMS
Lost Creek Reservoir Outflow (Lost Creek Res nr Jacksboro USGS gage)	28.8	240	890	1,600	4,500	7,200	10,200	12,700	15,900	Uniform HEC-HMS
Lost Creek above the West Fork	42.5	220	1,600	3,600	4,800	5,900	7,200	9,600	13,000	Uniform HEC-HMS
West Fork Trinity River below Lost Creek	711.2	2,200	6,400	12,000	21,300	31,600	49,600	67,100	94,500	Uniform HEC-HMS
West Fork Trinity River above Carroll Creek	750.8	2,200	6,500	12,300	21,500	31,900	49,900	67,400	94,800	Uniform HEC-HMS
West Fork Trinity River below Carroll Creek	792.1	2,200	7,200	18,700	27,700	35,300	50,300	67,800	95,400	Uniform HEC-HMS
West Fork Trinity River above Beans Creek	827.7	2,200	7,600	20,700	31,000	39,900	50,700	68,200	95,800	Uniform HEC-HMS
West Fork Trinity River below Beans Creek	874.6	1,700	11,600	26,900	38,900	49,700	62,900	74,300	93,300	Elliptical HEC-HMS
Bridgeport Reservoir Inflow	1095.7	3,700	24,500	58,400	83,000	105,500	132,300	157,200	192,200	Elliptical HEC-HMS
Bridgeport Reservoir Outflow	1095.7	2,600	5,400	11,600	12,400	13,200	21,100	29,300	39,000	Elliptical HEC-HMS
West Fork Trinity River above Dry Creek	1136.2	2,200	5,500	11,500	12,400	13,300	21,100	29,500	39,200	Elliptical HEC-HMS
West Fork Trinity River below Dry Creek	1162.9	1,800	5,900	12,600	17,500	21,800	26,700	31,400	37,800	Elliptical HEC-HMS
West Fork Trinity River above Big Sandy Creek	1169.5	1,800	5,300	11,800	17,200	22,300	27,600	32,500	39,200	Elliptical HEC-HMS
Amon G Carter Lake Outflow	109.5	170	620	1,200	1,500	4,600	10,300	14,800	24,800	Uniform HEC-HMS
Big Sandy Creek at Route 101 bridge near Sunset	151.5	1,900	4,600	7,000	10,200	12,800	15,700	18,400	31,000	Uniform HEC-HMS
Big Sandy Creek above Brushy Creek	192.2	1,400	3,700	5,900	10,100	14,200	19,400	23,800	33,600	Uniform HEC-HMS
Big Sandy Creek below Brushy Creek	262.8	2,400	6,500	10,300	17,300	24,200	33,400	41,500	53,100	Uniform HEC-HMS
Big Sandy Creek about 2 miles upstream of FM 1810	287.7	2,300	6,300	10,300	17,300	24,600	34,600	43,700	56,600	Uniform HEC-HMS

Location Description	Drainage Area*	50%	20%	10%	4%	2%	1%	0.50%	0.20%	Hydrologic Method
	sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR	
Big Sandy Creek nr Bridgeport USGS Gage at Hwy 114 bridge	334.3	2,700	7,100	11,600	19,100	26,600	37,800	48,100	65,000	Uniform HEC-HMS
Big Sandy Creek above the West Fork Trinity River	353.9	2,500	7,000	11,200	19,000	26,700	37,900	48,400	65,400	Uniform HEC-HMS
West Fork Trinity River below Big Sandy Creek	1523.5	4,400	11,200	19,700	28,200	36,600	49,000	61,100	78,400	Elliptical HEC-HMS
West Fork Trinity River at FM 3259 near Paradise, TX	1551.8	4,200	10,500	17,500	26,600	36,400	49,300	61,800	80,000	Elliptical HEC-HMS
West Fork Trinity River above Salt Creek	1573.7	3,600	9,700	15,300	22,800	31,700	44,500	56,600	74,800	Elliptical HEC-HMS
West Fork Trinity River below Salt Creek	1680.4	3,300	9,400	17,000	27,000	38,600	55,600	71,700	95,600	Elliptical HEC-HMS
West Fork Trinity River near Boyd, TX - USGS Gage at FM 730 bridge	1710.8	3,000	9,300	16,800	26,700	38,200	54,700	71,500	96,400	Elliptical HEC-HMS
West Fork Trinity River about 0.8 miles upstream of FM 4757 in Wise County	1751.9	3,200	9,800	16,700	26,300	37,400	53,300	69,000	92,900	Elliptical HEC-HMS
Walnut Creek at Reno, TX USGS gage at FM1542 bridge in Parker County	62.7	5,000	13,000	19,800	29,100	34,900	41,400	47,200	54,900	Uniform HEC-HMS
Walnut Creek above Eagle Mountain Lake in Tarrant County	81.4	2,600	8,300	14,300	25,000	32,000	40,100	46,800	55,400	Uniform HEC-HMS
Eagle Mountain Reservoir Inflow	1956.6	9,300	28,800	43,300	66,800	83,600	102,700	120,300	143,600	Elliptical HEC-HMS
Eagle Mountain Reservoir Outflow	1956.6	3,800	7,300	13,800	17,200	21,500	27,100	33,000	42,500	Elliptical HEC-HMS
Lake Worth Inflow	2050.8	4,800	11,800	16,500	25,400	31,200	37,800	43,500	51,500	Elliptical HEC-HMS
Lake Worth Outflow	2050.8	3,000	7,300	13,900	17,400	21,600	27,400	33,400	42,800	Elliptical HEC-HMS
West Fork Trinity River above the Clear Fork	2078.7	3,200	8,200	11,700	18,200	21,300	25,000	29,700	36,100	Elliptical HEC-HMS
Lake Weatherford Outflow	108.7	820	2,100	3,000	5,100	8,600	18,500	26,300	38,800	Uniform HEC-HMS
Clear Fork at Kelly Rd nr Aledo USGS gage	245.1	2,100	6,200	11,000	17,600	23,100	34,800	49,700	72,100	Uniform HEC-HMS
Clear Fork above Bear Creek	263.8	2,100	6,400	11,200	17,900	23,400	35,000	49,900	72,300	Uniform HEC-HMS
Benbrook Lake Inflow	429.2	16,300	43,700	61,600	82,500	99,100	118,000	135,900	163,700	Uniform HEC-HMS
Benbrook Lake Outflow (Clear Fork nr Benbrook)	429.2	3,000	6,000	6,000	6,000	6,000	6,700	9,900	14,600	Reservoir Study
Clear Fork above Marys Creek	9.4	4,300	7,800	10,000	12,500	14,300	16,200	18,100	20,800	Uniform HEC-HMS
Marys Creek at Benbrook USGS gage	54.2	2,500	12,400	25,100	43,500	52,700	63,100	77,000	92,500	Uniform HEC-HMS
Clear Fork below Marys Creek	63.6	4,000	13,200	26,700	46,800	56,700	68,700	83,500	100,800	Uniform HEC-HMS
Clear Fork Trinity River at Fort Worth USGS gage	89.0	5,700	17,000	31,500	53,200	62,600	72,100	83,800	99,400	Uniform HEC-HMS
Clear Fork Trinity River above the West Fork	93.9	6,200	17,100	30,800	50,200	59,700	69,500	80,000	93,900	Uniform HEC-HMS
West Fork Trinity River below the Clear Fork (West Fork at Fort Worth USGS gage)	2172.5	10,700	23,600	36,600	54,300	64,300	75,200	86,400	100,000	Elliptical HEC-HMS

Location Description	Drainage Area*	50%	20%	10%	4%	2%	1%	0.50%	0.20%	Hydrologic Method
	sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR	
West Fork Trinity River above Marine Creek	2173.7	10,700	24,000	36,900	53,500	63,400	73,700	86,500	100,200	Elliptical HEC-HMS
West Fork Trinity River below Marine Creek	2195.4	11,000	24,700	37,900	54,900	65,200	76,000	89,000	103,300	Elliptical HEC-HMS
West Fork Trinity River above Sycamore Creek	2204.6	11,300	24,000	37,800	53,900	62,600	73,700	88,000	104,400	Elliptical HEC-HMS
West Fork Trinity River below Sycamore Creek (West Fork Trinity River at Beach Street USGS Gage)	2243.8	11,500	23,700	36,900	56,100	66,700	77,200	90,400	108,400	Elliptical HEC-HMS
West Fork above Big Fossil	2256.8	10,200	21,400	34,600	53,200	64,400	76,000	89,000	107,100	Elliptical HEC-HMS
West Fork Trinity River and Big Fossil Creek Confluence	2333.4	12,300	23,700	38,000	60,600	76,400	92,700	108,500	130,200	Elliptical HEC-HMS
Village Creek at Everman USGS gage	90.4	7,400	14,300	20,200	27,200	33,000	39,700	46,100	54,800	Uniform HEC-HMS
Lake Arlington Inflow	143.1	13,000	24,600	31,700	40,900	48,500	56,400	64,300	75,100	Uniform HEC-HMS
Lake Arlington Outflow	143.1	2,300	3,500	3,600	4,900	10,500	18,700	26,800	37,500	Uniform HEC-HMS
Village Creek above West Fork	191.7	3,300	7,200	11,000	17,300	20,400	23,900	27,200	38,700	Uniform HEC-HMS
West Fork Trinity River below Village Creek	2554.0	11,700	21,100	36,400	55,000	70,200	89,200	108,600	138,800	Elliptical HEC-HMS
West Fork Trinity River below Johnson Creek	2618.6	8,600	17,200	27,000	44,000	58,300	78,100	96,800	129,200	Elliptical HEC-HMS
West Fork Trinity River at Grand Prairie USGS gage	2623.4	8,500	17,200	27,100	44,200	58,400	78,000	96,500	128,100	Elliptical HEC-HMS
West Fork Trinity River above Big Bear Creek	2625.5	8,400	16,500	26,400	42,600	56,700	73,200	93,000	124,500	Elliptical HEC-HMS
West Fork Trinity River below Big Bear Creek	2718.8	10,000	17,600	29,700	50,000	66,800	85,300	107,200	143,000	Elliptical HEC-HMS
West Fork Trinity River above Mountain Creek	2727.4	10,000	17,500	29,100	46,200	62,600	81,600	101,600	134,400	Elliptical HEC-HMS
Walnut Creek near Mansfield, TX USGS gage	62.9	4,100	8,100	11,600	17,100	20,900	25,300	29,800	35,100	Uniform HEC-HMS
Walnut Creek above Joe Pool Lake	67.2	4,000	7,900	11,300	16,700	20,500	25,000	29,400	34,700	Uniform HEC-HMS
Mountain Ck near Venus, TX USGS Gage	26.0	3,600	6,700	8,800	11,600	13,900	16,500	18,900	22,300	Uniform HEC-HMS
Joe Pool Lake Inflow	224.2	14,100	27,500	38,500	54,600	67,300	82,500	97,400	116,200	Uniform HEC-HMS
Joe Pool Lake Outflow	224.2	1,200	2,400	4,000	4,000	4,000	4,000	4,000	4,000	Reservoir Study
Mountain Creek Lake Inflow	70.6	20,600	32,800	40,400	50,200	57,800	66,000	74,300	85,300	Uniform HEC-HMS
Mountain Creek Lake Outflow	70.6	11,900	21,700	29,700	40,500	48,000	56,600	63,800	69,400	Uniform HEC-HMS
Mountain Creek above the West Fork Trinity River	80.2	8,800	15,500	20,400	26,700	31,900	38,300	44,600	52,600	Uniform HEC-HMS
West Fork Trinity River below Mountain Creek	2807.6	14,100	22,900	30,300	47,300	63,900	82,900	103,100	137,000	Elliptical HEC-HMS
West Fork Trinity River above the Elm Fork Trinity River	2820.9	13,100	21,700	29,900	46,800	63,600	83,000	103,100	136,100	Elliptical HEC-HMS
Elm Fork Trinity River above Brushy Elm Creek	67.4	2,600	5,200	7,900	12,800	17,700	24,100	30,500	38,900	Uniform HEC-HMS
Muenster Lake Outflow	14.0	200	330	340	360	370	510	790	1,200	Uniform HEC-HMS

Location Description	Drainage Area*	50%	20%	10%	4%	2%	1%	0.50%	0.20%	Hydrologic Method
	sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR	
Brushy Elm Creek above the Elm Fork Trinity River	25.5	1,800	3,600	4,900	6,500	7,700	9,100	10,500	12,400	Uniform HEC-HMS
Elm Fork Trinity River below Brushy Elm Creek	92.9	3,300	6,800	10,000	15,600	20,800	27,500	34,500	43,800	Uniform HEC-HMS
Elm Fork Trinity River below Dry Elm Creek	137.0	6,200	13,200	19,500	28,500	36,400	45,600	54,800	67,300	Uniform HEC-HMS
Elm Fk Trinity Rv at Gainesville, TX USGS gage	177.2	8,300	18,100	26,500	38,300	48,400	60,400	71,900	87,500	Uniform HEC-HMS
Elm Fork Trinity River below Pecan Creek	216.8	8,100	18,100	27,000	39,700	50,800	64,200	77,200	94,200	Uniform HEC-HMS
Elm Fork Trinity River above Ray Roberts Lake	265.0	7,600	17,200	25,800	38,400	49,700	64,100	77,800	95,600	Uniform HEC-HMS
Lake Kiowa Inflow	16.8	1,900	5,000	6,900	9,200	11,000	13,000	15,000	17,600	Uniform HEC-HMS
Lake Kiowa Outflow	16.8	450	1,500	2,300	3,600	4,700	5,900	7,200	8,900	Uniform HEC-HMS
Timber Ck nr Collinsville, TX USGS gage	39.0	2,600	7,500	10,800	14,900	18,200	22,000	25,600	30,500	Uniform HEC-HMS
Timber Creek above Ray Roberts Lake	64.2	4,000	10,300	15,000	20,800	25,500	31,100	36,200	43,100	Uniform HEC-HMS
Range Creek nr Collinsville, TX USGS gage	29.3	2,700	8,300	12,900	20,400	24,000	28,000	31,700	36,700	Uniform HEC-HMS
Range Creek above Ray Roberts Lake	50.6	2,800	6,900	10,400	17,400	21,200	25,600	29,400	34,700	Uniform HEC-HMS
Ray Roberts Lake Inflow	692.6	59,500	95,900	120,600	153,100	182,400	216,100	249,700	296,000	Elliptical HEC-HMS
Ray Roberts Lake Outflow (Elm Fork at Greenbelt nr Pilot Point USGS gage)	692.6	2,000	4,000	7,000	7,000	7,000	7,000	7,000	7,000	Reservoir Study
Elm Fork Trinity River above Clear Creek	36.9	2,000	4,800	9,000	12,000	14,400	17,200	19,700	23,200	Uniform HEC-HMS
Clear Creek above Bingham Creek	83.9	2,500	4,700	8,800	15,200	21,100	28,400	35,500	44,200	Uniform HEC-HMS
Clear Creek below Bingham Creek	99.9	2,600	5,100	9,700	17,200	24,000	32,500	40,700	50,800	Uniform HEC-HMS
Clear Creek above Williams Creek	151.6	3,200	5,300	10,100	18,600	26,800	37,300	47,300	60,000	Uniform HEC-HMS
Clear Creek below Williams Creek	187.2	4,400	7,400	13,500	24,000	34,000	46,800	59,200	74,700	Uniform HEC-HMS
Clear Creek below Flat Creek	214.5	4,600	8,700	16,300	28,300	39,300	53,400	67,100	84,400	Uniform HEC-HMS
Clear Creek above Duck Creek	259.5	5,100	9,200	17,000	29,700	41,500	56,900	71,900	90,400	Uniform HEC-HMS
Clear Ck nr Sanger, TX USGS gage	294.6	6,000	10,400	19,000	32,800	45,700	62,600	78,900	99,300	Uniform HEC-HMS
Clear Creek above Moores Branch	309.9	5,600	9,500	16,500	29,500	42,500	59,700	76,300	97,200	Uniform HEC-HMS
Clear Creek below Moores Branch	322.8	5,700	9,600	16,700	29,800	43,000	60,400	77,400	98,600	Uniform HEC-HMS
Clear Creek above the Elm Fork Trinity River	351.2	5,300	9,100	15,800	28,900	42,500	60,600	78,300	100,600	Uniform HEC-HMS
Elm Fork Trinity River below Clear Creek	388.1	5,300	9,300	16,100	29,400	43,300	62,100	80,500	104,000	Uniform HEC-HMS
Little Elm Ck nr Aubrey, TX USGS gage	72.9	3,400	7,400	10,400	15,200	19,500	24,700	29,500	35,700	Uniform HEC-HMS
Little Elm Creek below Mustang Creek	95.8	4,100	8,700	12,300	18,000	23,100	29,300	35,100	42,500	Uniform HEC-HMS

Location Description	Drainage Area*	50%	20%	10%	4%	2%	1%	0.50%	0.20%	Hydrologic Method
	sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR	
Doe Br at Hwy 380 nr Prosper, TX USGS gage	38.4	4,200	7,200	9,500	12,500	14,900	17,700	20,300	23,800	Uniform HEC-HMS
Doe Branch above Little Elm Creek	71.0	6,500	11,600	15,400	20,700	24,800	29,600	34,000	40,100	Uniform HEC-HMS
Little Elm below Doe Branch	231.3	8,900	17,900	24,800	34,100	41,800	51,200	60,000	72,500	Uniform HEC-HMS
Hickory Creek below North & South Hickory Creek confluence	80.7	7,700	16,400	22,600	30,000	36,000	42,700	48,800	57,200	Uniform HEC-HMS
Hickory Creek at Denton, TX USGS gage	128.9	6,200	13,600	19,100	26,400	32,700	40,300	46,900	55,800	Uniform HEC-HMS
Hickory Creek at Old Alton Rd above Lewisville Lake	148.9	5,900	12,500	18,000	25,200	31,700	39,400	46,600	55,900	Uniform HEC-HMS
Lewisville Lake Inflow	968.2	42,500	69,000	88,200	112,500	135,100	159,700	182,700	215,000	Elliptical HEC-HMS
Lewisville Lake Outflow (Elm Fork nr Lewisville USGS gage)	968.2	4,000	7,000	7,000	9,400	17,900	26,500	36,000	50,000	Reservoir Study
Elm Fork Trinity River above Indian Creek	21.4	4,000	7,000	7,000	9,400	17,900	26,500	36,000	50,000	Reservoir Study
Elm Fort Trinity River below Indian Creek	37.5	4,000	7,000	9,200	14,400	17,900	26,500	36,000	50,000	Reservoir Study/Uniform HEC-HMS
Elm Fork Trinity River below Timber Creek	61.5	4,000	7,000	9,700	14,800	17,900	26,500	36,000	50,000	Reservoir Study/Uniform HEC-HMS
Elm Fork Trinity River above Denton Creek	79.9	5,200	9,100	12,900	19,300	22,900	27,500	36,000	50,000	Reservoir Study/Uniform HEC-HMS
Denton Creek above FM 1655	116.0	3,700	8,700	14,000	20,700	26,800	32,900	41,500	52,600	Uniform HEC-HMS
Denton Creek above Sweetwater Creek	285.1	5,400	12,600	20,200	29,500	38,300	46,800	58,800	71,800	Uniform HEC-HMS
Denton Creek below Sweetwater Creek	346.6	6,200	14,200	22,900	34,200	44,900	55,600	70,000	86,500	Uniform HEC-HMS
Denton Creek nr Justin, TX USGS gage	400.0	4,100	9,700	16,000	26,000	35,900	47,300	62,900	81,700	Uniform HEC-HMS
Denton Creek below Oliver Creek	475.3	6,100	15,500	24,100	35,400	44,600	54,800	70,100	92,700	Uniform HEC-HMS
Denton Creek above Elizabeth Creek	506.1	6,800	15,500	23,300	35,200	45,600	57,200	70,400	94,200	Uniform HEC-HMS
Denton Creek below Elizabeth Creek	599.7	15,800	29,300	39,500	53,400	68,400	85,300	102,000	123,900	Elliptical HEC-HMS
Grapevine Lake Inflow	694.4	16,000	28,200	38,600	52,200	66,900	84,800	101,600	124,500	Elliptical HEC-HMS
Grapevine Lake Outflow (Denton Creek nr Grapevine USGS gage)	694.4	2,000	2,000	2,000	3,100	7,700	13,100	20,100	30,800	Reservoir Study
Denton Creek above the Elm Fork Trinity River	24.3	2,100	4,100	6,100	10,400	12,200	14,300	20,100	30,800	Reservoir Study/Uniform HEC-HMS
Elm Fork Trinity River near Carrollton USGS gage	104.2	6,700	11,700	17,100	26,700	31,500	37,200	43,200	51,200	Uniform HEC-HMS
Elm Fork Trinity River at Interstate 635	143.4	11,400	17,500	21,900	30,500	36,600	43,300	50,100	59,600	Uniform HEC-HMS

Location Description	Drainage Area*	50%	20%	10%	4%	2%	1%	0.50%	0.20%	Hydrologic Method
	sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR	
Elm Fork Trinity River above Hackleberry Creek	143.4	8,300	13,300	18,300	29,100	35,200	42,100	49,000	57,200	Uniform HEC-HMS
Elm Fk Trinity Rv at Spur 348 in Irving; TX USGS gage	180.4	10,000	15,000	19,100	30,300	37,100	45,100	52,800	62,400	Uniform HEC-HMS
Elm Fork Trinity River above Bachman Branch	202.6	9,100	14,100	17,900	27,100	33,700	41,700	48,500	57,700	Uniform HEC-HMS
Bachman Lake Outflow	12.7	3,100	6,000	8,100	11,200	13,400	16,000	18,600	21,600	Uniform HEC-HMS
Bachman Branch above the Elm Fork Trinity River	14.1	1,600	3,000	4,000	5,300	6,400	7,800	9,200	11,200	Uniform HEC-HMS
Elm Fork Trinity River below Bachman Branch (at Frasier Dam USGS gage)	216.7	10,000	15,600	19,200	27,500	34,400	42,600	49,600	58,900	Uniform HEC-HMS
Elm Fork Trinity River above the West Fork Trinity River	222.8	8,100	13,400	18,100	26,800	33,700	41,800	48,800	58,700	Uniform HEC-HMS
Trinity River below the West Fork and Elm Fork confluence	3043.7	19,300	31,100	41,900	67,100	89,600	113,800	140,200	182,800	Elliptical HEC-HMS
Trinity River at Dallas, TX USGS gage	3056.1	19,000	31,000	42,100	66,200	88,500	113,100	138,900	181,500	Elliptical HEC-HMS
Trinity River at the Corinth Street bridge in Dallas, TX	3099.0	19,000	31,000	42,200	66,300	88,500	113,500	139,100	182,300	Elliptical HEC-HMS
White Rock Creek at Greenville Ave USGS gage	66.7	16,300	24,400	30,800	39,500	45,900	52,900	59,600	68,700	Uniform HEC-HMS
White Rock Lake Inflow	95.0	13,200	20,400	25,300	33,300	39,600	46,600	53,200	62,200	Uniform HEC-HMS
White Rock Lake Outflow	95.0	9,800	15,300	19,800	26,400	31,900	38,000	43,800	51,900	Uniform HEC-HMS
White Rock Creek above the Trinity River	134.9	9,100	16,300	20,800	26,100	30,400	35,000	39,600	46,100	Uniform HEC-HMS
Trinity River below White Rock Creek	3233.9	21,800	35,500	48,000	68,200	90,000	116,800	143,700	185,500	Elliptical HEC-HMS
Trinity River below Honey Springs Branch (Trinity River below Dallas, TX USGS gage)	3256.5	21,900	35,700	48,300	68,400	90,000	116,700	143,800	185,700	Elliptical HEC-HMS
Trinity River below Five Mile Ceek	3328.8	21,100	34,600	47,300	67,600	88,000	114,100	140,200	180,300	Elliptical HEC-HMS
Trinity River above Ten Mile Creek	3367.7	20,100	29,900	40,700	59,400	78,800	104,000	125,700	161,300	Elliptical HEC-HMS
Trinity River below Ten Mile Creek	3469.8	20,200	30,800	40,600	59,300	78,500	103,700	124,800	160,400	Elliptical HEC-HMS
Trinity River above the East Fork Trinity River	3529.4	19,500	28,400	37,700	56,700	74,900	99,500	122,800	156,000	Elliptical HEC-HMS
East Fork Trinity River below Honey Creek	167.9	4,100	7,600	11,300	17,700	23,600	31,000	38,000	47,200	Uniform HEC-HMS
East Fork Trinity River near McKinney, TX USGS gage	190.1	4,600	8,500	12,500	19,300	25,600	33,800	41,400	51,400	Uniform HEC-HMS
East Fork Trinity River above Wilson Creek	214.8	4,600	8,600	12,500	19,100	25,300	33,500	41,200	51,400	Uniform HEC-HMS
East Fork Trinity River below Wilson Creek	292.3	7,100	12,600	18,000	26,700	34,800	45,500	55,500	68,900	Uniform HEC-HMS
Sister Grove Creek near Blue Ridge USGS gage	83.2	1,400	2,800	4,100	6,400	8,400	11,000	13,400	16,500	Uniform HEC-HMS
Sister Grove Creek above Indian Creek	121.2	2,400	4,600	6,400	8,900	11,000	13,500	15,900	19,600	Uniform HEC-HMS
Indian Creek at SH 78 nr Farmersville, TX USGS gage	104.6	2,400	4,200	6,000	8,800	11,200	14,300	17,300	21,200	Uniform HEC-HMS

Location Description	Drainage Area*	50%	20%	10%	4%	2%	1%	0.50%	0.20%	Hydrologic Method
	sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR	
Indian Creek below Pilot Grove Creek	205.8	4,400	8,800	12,600	18,400	23,400	29,800	35,800	43,800	Uniform HEC-HMS
Indian Creek above Sister Grove Creek	235.9	4,700	9,300	13,300	19,500	24,900	32,100	38,600	47,300	Uniform HEC-HMS
Indian Creek below Sister Grove Creek	357.1	6,200	12,300	17,600	26,200	33,800	44,100	53,500	66,100	Uniform HEC-HMS
Lavon Lake Inflow	768.2	24,100	42,300	53,600	69,400	79,900	90,700	106,400	128,700	Elliptical HEC-HMS
Lake Lavon Outflow	768.2	4,000	8,000	8,000	10,700	22,000	35,200	49,300	66,000	Reservoir Study
Rowlett Creek near Sachse, TX USGS gage	119.9	13,500	25,400	35,200	46,600	54,600	63,600	72,100	83,800	Uniform HEC-HMS
Ray Hubbard Lake Inflow	301.8	24,600	42,200	56,900	75,600	90,300	107,300	123,300	145,100	Uniform HEC-HMS
Ray Hubbard Lake Outflow (East Frk blw Ray Hubbard Data)	301.8	8,900	16,500	26,000	38,000	47,400	59,800	83,300	101,300	Uniform HEC-HMS
East Fork Trinity River near Forney USGS gage	349.9	10,500	19,500	30,300	44,100	55,000	69,300	95,500	117,100	Uniform HEC-HMS
East Fork Trinity River above Buffalo Creek	359.5	9,300	17,800	26,500	40,800	52,700	67,400	91,700	115,500	Uniform HEC-HMS
East Fork Trinity River below Buffalo Creek	393.9	9,900	18,900	28,300	42,900	55,800	71,900	97,900	123,600	Uniform HEC-HMS
East Fork Trinity River above South Mesquite Creek	416.9	7,700	15,500	24,000	36,000	48,100	64,000	82,200	111,600	Uniform HEC-HMS
East Fork Trinity River below South Mesquite Creek	446.4	8,100	16,300	25,200	37,500	50,300	67,000	86,800	117,600	Uniform HEC-HMS
East Fork Trinity River above Mustang Creek	465.5	8,000	15,100	23,000	32,600	43,400	57,200	72,200	96,100	Uniform HEC-HMS
East Fork Trinity River near Crandall, TX USGS gage	484.8	8,200	15,500	23,500	33,200	44,300	58,400	73,900	98,300	Uniform HEC-HMS
East Fork Trinity River above the Trinity River	484.8	8,000	14,100	20,600	28,700	37,100	48,600	59,700	75,100	Uniform HEC-HMS
Trinity River below the East Fork Trinity River	4014.2	27,000	41,600	54,200	80,400	104,100	134,200	166,200	210,600	Elliptical HEC-HMS
Trinity River below Red Oak Creek	4245.5	27,100	43,400	55,300	81,000	105,000	135,200	167,700	212,700	Elliptical HEC-HMS
Trinity River near Rosser, TX USGS gage	4349.6	25,600	38,900	51,000	74,000	98,700	131,500	164,600	207,300	Elliptical HEC-HMS
Trinity River above Cedar Creek	4349.6	24,700	38,000	50,000	68,300	76,700	105,600	150,100	196,600	Elliptical HEC-HMS
Kings Creek at SH34 near Kaufman, TX USGS gage	222.6	3,800	7,400	10,500	15,300	19,900	25,900	31,500	39,500	Uniform HEC-HMS
Kings Creek above Cedar Creek Reservoir	343.1	6,000	10,600	15,000	22,600	29,200	37,200	45,200	56,200	Uniform HEC-HMS
Cedar Creek near Kemp, TX USGS gage	190.1	5,400	8,400	10,900	14,600	17,100	22,200	27,100	34,100	Uniform HEC-HMS
Cedar Creek above Cedar Creek Reservoir	283.5	5,900	11,600	16,300	22,400	27,500	33,800	39,700	48,000	Uniform HEC-HMS
Cedar Creek Reservoir Inflow	1010.8	45,200	82,100	106,000	135,000	158,200	182,100	219,900	274,400	Elliptical HEC-HMS
Cedar Creek Reservoir Outflow	1010.8	32,400	55,600	70,000	88,300	105,900	123,700	129,800	140,500	Elliptical HEC-HMS
Trinity River below Cedar Creek	5360.4	27,600	41,300	53,400	71,600	79,200	112,300	162,400	220,600	Elliptical HEC-HMS
Trinity River at Trinidad, TX USGS gage	5759.3	33,300	51,200	68,000	89,100	106,800	125,100	155,800	188,200	Elliptical HEC-HMS

Location Description	Drainage Area*	50%	20%	10%	4%	2%	1%	0.50%	0.20%	Hydrologic Method
	sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR	
Trinity River above Richland Creek	6042.8	31,300	48,100	63,500	83,100	99,900	117,300	149,800	187,500	Elliptical HEC-HMS
Waxahachie Creek at Waxahachie	60.4	1,500	4,400	8,900	15,500	20,900	27,500	34,000	42,800	Uniform HEC-HMS
Lake Waxahachie Outflow	30.6	1,700	3,900	5,900	8,700	12,000	15,600	17,400	26,400	Uniform HEC-HMS
Waxahachie Creek below Lake Waxahachie	91.0	2,600	6,400	11,700	19,400	25,500	33,500	42,000	52,000	Uniform HEC-HMS
Mustang Creek above Bardwell Lake	29.9	3,600	6,600	8,700	11,600	14,000	16,700	19,400	23,200	Uniform HEC-HMS
Bardwell Lake Inflow	174.4	9,200	16,700	22,000	29,200	35,200	42,300	49,400	62,400	Uniform HEC-HMS
Bardwell Lake Outflow	174.4	1,200	2,000	2,000	2,000	2,000	4,300	5,700	9,500	Reservoir Study
Chambers Creek below North Fork and South Fork Chambers Creek	308.4	11,000	20,600	29,700	41,200	53,900	69,700	84,700	104,400	Uniform HEC-HMS
Chambers Creek below Mill Creek	511.9	13,600	29,100	40,900	62,200	75,900	88,300	114,200	148,800	Elliptical HEC-HMS
Chambers Creek below Waxahachie Creek	621.0	12,800	28,300	39,500	60,200	74,300	86,700	113,500	152,700	Elliptical HEC-HMS
Chambers Creek near Rice, TX USGS gage	650.1	12,500	28,000	39,000	59,200	73,300	88,100	110,500	148,800	Elliptical HEC-HMS
White Rock Creek at FM 308 near Irene, TX USGS gage	65.8	3,600	8,100	12,400	19,000	24,600	31,300	37,800	46,300	Uniform HEC-HMS
Navarro Mille Lake Inflow	319.9	11,600	23,900	34,200	49,900	63,200	79,900	96,100	121,700	Uniform HEC-HMS
Navarro Mills Lake Outflow	319.9	1,000	2,000	2,000	3,000	7,000	9,900	14,000	21,000	Reservoir Study
Richland Creek below Pin Oak Creek	395.0	12,700	26,700	39,700	60,700	78,700	100,800	123,100	155,900	Uniform HEC-HMS
Richland Chambers Reservoir Inflow	1465.5	33,300	64,300	85,700	112,000	133,000	154,500	188,200	237,200	Elliptical HEC-HMS
Richland Chambers Reservoir Outflow	1465.5	13,100	25,900	37,400	62,600	91,800	111,300	141,200	193,000	Reservoir Study
Trinity River below Richland Creek	7508.3	36,200	64,300	88,100	122,800	150,100	177,200	234,800	304,000	Elliptical HEC-HMS
Trinity River above Tehuacana Creek	7508.3	35,300	63,300	87,600	122,400	149,500	178,100	234,200	306,200	Elliptical HEC-HMS
Tehuacana Creek near Streetman, TX USGS gage	141.3	7,100	15,000	20,400	34,100	43,700	55,100	66,200	81,900	Uniform HEC-HMS
Tehuacana Creek above the Trinity River	386.4	7,900	15,100	22,400	38,200	52,900	72,500	91,900	118,800	Uniform HEC-HMS
Trinity River below Tehuacana Creek	7894.7	38,700	59,000	81,700	124,000	157,800	192,800	259,200	349,800	Elliptical HEC-HMS
Trinity River above Big Brown Creek	7965.3	37,900	58,600	80,900	120,000	148,400	189,000	254,100	345,000	Elliptical HEC-HMS
Trinity River below Big Brown Creek	8001.5	38,200	59,100	81,600	121,000	154,000	190,100	255,900	348,700	Elliptical HEC-HMS
Trinity River above Catfish Creek	8306.6	39,500	60,800	85,300	122,200	153,300	190,100	264,300	367,200	Elliptical HEC-HMS
Trinity River below Catfish Creek	8353.0	39,800	61,400	86,000	123,200	154,200	191,500	266,400	370,700	Elliptical HEC-HMS
Trinity River near Oakwood, TX USGS gage	8593.0	36,300	59,500	81,100	107,400	129,000	152,400	223,500	308,900	Elliptical HEC-HMS
Trinity River above Upper Keechi Creek	8849.7	33,000	54,300	71,800	99,000	121,800	139,500	160,100	235,500	Elliptical HEC-HMS

Location Description	Drainage Area*	50%	20%	10%	4%	2%	1%	0.50%	0.20%	Hydrologic Method
	sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR	
Upper Keechi Creek near Oakwood, TX USGS gage	150.3	3,400	11,400	19,500	31,100	39,200	48,900	58,300	72,000	Uniform HEC-HMS
Upper Keechie Creek above Buffalo Creek	186.8	3,000	10,500	18,000	29,100	37,200	47,100	56,800	70,900	Uniform HEC-HMS
Upper Keechie Creek below Buffalo Creek	459.5	5,800	21,000	35,000	54,400	69,900	89,300	109,400	135,700	Uniform HEC-HMS
Upper Keechie Creek above the Trinity River	509.2	5,700	20,100	33,400	51,900	66,900	86,100	106,000	132,200	Uniform HEC-HMS
Trinity River below Upper Keechi Creek	9358.9	33,700	54,900	72,200	99,700	122,900	140,900	163,700	243,300	Elliptical HEC-HMS
Trinity River above Big Elkhart Creek	9359.5	33,600	54,300	72,000	99,500	122,800	140,700	163,600	241,800	Elliptical HEC-HMS
Houston County Lake Ouflow	48.0	110	220	420	900	1,600	4,700	7,900	12,700	Uniform HEC-HMS
Big Elkhart Creek above the Trinity River	143.0	2,000	6,500	10,000	14,700	18,900	25,300	33,100	43,500	Uniform HEC-HMS
Trinity River below Big Elkhart Creek	9502.5	33,100	53,300	70,100	98,000	121,600	139,300	160,600	233,700	Elliptical HEC-HMS
Trinity River near Crockett, TX USGS gage	9615.0	33,300	53,900	71,500	98,700	121,900	139,800	160,600	235,000	Elliptical HEC-HMS
Trinity River above Lower Keechi Creek	9791.7	32,900	48,100	56,600	72,500	96,400	114,900	145,300	181,300	Elliptical HEC-HMS
Trinity River below Lower Keechi Creek	9979.3	32,700	48,200	56,600	72,600	96,700	115,200	145,500	181,500	Elliptical HEC-HMS
Trinity River above Bedias Creek	10374.29	32,600	47,200	54,300	68,600	92,800	110,200	140,400	175,800	Elliptical HEC-HMS
Bedias Creek near Madisonville, TX USGS gage	330.6	8,200	16,200	24,400	38,000	47,500	65,100	82,300	105,800	Uniform HEC-HMS
Bedias Creek above the Trinity River	604.3	11,900	25,800	38,600	59,000	74,700	100,900	126,500	162,400	Uniform HEC-HMS
Trinity River below Bedias Creek	10978.5	44,300	69,800	96,100	128,000	150,400	172,300	205,200	251,400	Elliptical HEC-HMS
Trinity River at Riverside, TX USGS gage	11306.7	41,000	61,500	71,800	109,300	133,800	158,700	194,300	249,200	Elliptical HEC-HMS
Lake Livingston Inflow	12301.1	77,000	111,100	144,000	193,600	233,400	278,700	333,900	413,400	Elliptical HEC-HMS
Lake Livingston Outflow	12301.1	38,900	65,700	81,100	100,400	120,700	158,200	210,400	281,800	Elliptical HEC-HMS
Trinity River above Long King Creek	12340.5	39,600	67,000	82,800	102,100	123,700	159,400	208,300	277,000	Elliptical HEC-HMS
Long King Creek at Livingston, TX USGS gage	141.1	5,700	13,600	19,700	28,700	36,500	46,300	55,800	69,400	Uniform HEC-HMS
Long King Creek above the Trinity River	226.4	7,500	17,000	25,000	37,300	48,200	62,000	75,200	94,300	Uniform HEC-HMS
Trinity River at Goodrich, TX USGS gage	12566.9	40,000	69,000	84,400	104,700	126,400	162,200	211,200	282,700	Elliptical HEC-HMS
Trinity River above Menard Creek	12628.0	39,400	59,900	73,600	89,400	101,100	118,200	148,200	207,300	Elliptical HEC-HMS
Menard Creek near Rye, TX USGS gage	148.1	2,300	6,300	10,000	15,600	20,800	27,900	34,700	44,400	Uniform HEC-HMS
Trinity River below Menard Creek	12776.2	40,700	64,000	77,400	94,100	107,700	127,500	159,500	220,900	Elliptical HEC-HMS
Trinity River at Romayor, TX USGS gage	12873.7	40,700	62,900	76,500	93,100	107,000	126,200	157,100	218,100	Elliptical HEC-HMS
Trinity River near Moss Hill, TX, about 3 miles downstream of FM 105 bridge	12945.7	39,600	59,200	73,800	91,300	104,600	122,000	152,200	208,800	Elliptical HEC-HMS

Location Description	Drainage Area*	50%	20%	10%	4%	2%	1%	0.50%	0.20%	Hydrologic Method
	sq mi	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	200-YR	500-YR	
Trinity River at Liberty, TX USGS gage	13176.5	34,800	54,500	70,800	90,200	103,700	120,900	151,100	205,300	Elliptical HEC-HMS
Trinity River at Wallisville, TX USGS gage	13618.4	32,300	45,700	62,400	84,000	98,700	115,300	141,800	188,300	Elliptical HEC-HMS

*Drainage area is uncontrolled area downstream of USACE dams.

12 Conclusions

Previous FEMA Flood Insurance Studies (FIS) in the Trinity River Basin differ from the new flow frequency results of this study in several locations. The new flow frequency results are higher than the effective results in some areas, while they are lower in other areas. The changes to the flow frequency estimates can primarily be attributed to a combination of factors including (1) additional gage record length, (2) better calibration of the watershed model, (3) use of additional hydrologic methods, and (4) increased urbanization in Dallas-Fort Worth. First, the new flow frequency results from this study differ from the effective flood insurance values because there have been new floods in the gage record, causing some of the statistical estimates to be very different than they were in the 1970s and 1980s when much of the FEMA effective flow frequency estimates in the Trinity River basin were developed. As mentioned previously and illustrated in Section 5.3, 300-400 years of record are needed before the 1% annual chance (100-yr) flow frequency estimates will stop significantly changing over time with additional years of record, unless additional information such as rainfall-runoff modeling estimates are utilized in the statistical analysis. Second, the rainfall-runoff watershed model underwent extensive calibration to accurately simulate the response of the watershed to a range of recent observed flood events, including large events similar to a 1% annual chance (100-yr) flood. The frequency flow results of the calibrated rainfall-runoff watershed model exposed that some of the values calculated in the past using statistical hydrology and uncalibrated rainfall-runoff modeling were not reasonable and did not accurately reflect the response of the watershed to a 1% annual chance (100-yr) storm event. Third, the use of additional hydrologic methods such as the USACE reservoir study stochastic modeling techniques using RMC-RFA resulted in improved stage and flow frequency estimates at and below the reservoirs. Finally, increased urbanization in the Dallas Fort Worth metroplex led to higher discharges along some reaches, when compared to the results of studies from the 1980s.

The flow results that were recommended for adoption came from a combination of the NOAA Atlas 14 watershed model results using uniform rain, elliptical storms, and USACE reservoir study techniques. Other methods, such as the statistical and Riverware results, were used as points of comparison to fine tune the model for the frequent storms, but they were not adopted directly due to their tendency to change after each significant flood event. Since the calibrated watershed model simulates the physical processes that occur during a storm event, it can produce more reliable and consistent estimations of the flow expected during a 1% annual chance (100-yr) storm. In addition, NOAA Atlas 14 shed new light on the depths and frequency of rainfall that could be expected in the Trinity basin. Both uniform rain and elliptical shaped frequency storms were run in the watershed model. The elliptical frequency storm results were generally recommended for certain river reaches with large drainage areas, while the uniform rain results were recommended for the smaller drainage areas. Dam operations for Benbrook, Bardwell, Grapevine, Joe Pool, Lavon, Lewisville, Navarro Mills, Ray Roberts, and Richland-Chambers were also examined in detail for this study, and the frequency dam releases and pool elevations that resulted from that reservoir study were recommended for the reaches immediately upstream and downstream of the dam.

Given the severe loss of life and property that occurred during recent floods within the State, it is imperative that future updates to the flood insurance rate maps for the Trinity River Basin accurately reflect the known levels of flood risk in the basin. The recommended flows represent the best available estimate of flood risk for the larger rivers in the Trinity basin based on a range of hydrologic methods performed by an expert team of engineers and scientists from multiple federal agencies. For the smaller tributaries, the new flows from the watershed model provide a good starting point which could be further refined by adding additional subbasins and using methodologies that are consistent with this study. The updated flows presented in this report can be used to revise flood insurance rate maps to help inform residents on flood risk impacts, which is important for the protection of life and property.

As a result of the level of investment, analyses, and collaboration that went into this Trinity Watershed Hydrology Assessment, the flood risk estimates contained in this report are recommended as the basis for future NFIP studies or other federal flood risk studies. These federally developed modeling results form a consistent understanding of hydrology across the Trinity Watershed, a key requirement outlined in FEMA's General Hydrologic Considerations Guidance. The modeling used to produce these flood risk estimates is available, at no charge, to communities and AE firms.

While the results from this study are considered a good starting point or even the best available estimates of flood risk for some areas, significant uncertainty still remains in the estimates as it does in any hyrdrologic study. Because of this uncertainty and because of the potential impacts these estimates can have on life and property, the InFRM team strongly recommends and supports local communities that implement higher standards, such as additional freeboard requirements, floodplain management practices that use frequency estimates greater than the 1% annual chance estimates, or "No valley storage loss" criteria.

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14 Terms of Reference

BFE	base flood elevations
cfs	cubic feet per second
CWMS	Corps Water Management System
DDF	Depth Duration Frequency
DEM	digital elevation model
DSS	data storage system
EM	Engineering Manual
EMA	expected moment algorithm
ERDC	Engineering Research & Development Center of USACE
FEMA	Federal Emergency Management Agency
FIS	flood insurance study
GeoHMS	Geospatial Hydrologic Model System extension
GIS	Geographic Information Systems
HEC	Hydrologic Engineering Center
HMS	Hydrologic Modeling System
IACWD	Interagency Advisory Committee on Water Data
InFRM	Interagency Flood Risk Management
LiDAR	Light (Laser) Detection and Range
LOC	Line of organic correlation
LPIII	Log Pearson III
MMC	Modeling, Mapping, and Consequences Production Center
NA14	NOAA Atlas 14
NAD 83	North American Datum of 1983
NCDC	National Climatic Data Center
NED	National Elevation Dataset
NGVD 29	National Geodetic Vertical Datum of 1929
NHD	National Hydrography Dataset
NID	National Inventory of Dams
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NWIS	National Water Information System
NWS	National Weather Service
PDSI	Palmer Drought Severity Index
PeakFQ	Peak Flood Frequency
PFDS	Precipitation Frequency Data Server
QPF	Quantitative Precipitation Forecast
RAS	River Analysis System
ResSIM	Reservoir System Simulation
RFC	River Forecast Center
SCS	Soil Conservation Service
SHG	Standard Hydrologic Grid
SI	Structure Inventory
SME	subject matter expert
SOP	Standard Operating Procedures
sq mi	square miles
SSURGO	Soil Survey Geographic Database
TLS	Total-Least Squares
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WCM	Water Control Manual
WGRFC	West Gulf River Forecast Center