COMPARATIVE ANALYSIS OF FLOOD FREQUENCY BASED ON RADAR-BASED PRECIPITATION DATA AND PRECIPITATION TRENDS

by

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Abstract

COMPARATIVE ANALYSIS OF FLOOD FREQUENCY

BASED ON RADAR-BASED PRECIPITATION

DATA AND PRECIPITATION TRENDS

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This study utilizes radar-based precipitation data from the National Weather Service West Gulf River Forecast Center to extract the depth-area-duration relationships via the U.S. Army Corps of Engineers' software HEC-MetVue. Extreme storms from 1996-2013 were analyzed to determine the characteristics for synthetic design storms. Design storms of 10-, 25-, 50- and 100-year return periods were developed and simulated using the U.S. Army Corps of Engineers' hydrologic modeling tool, HEC-HMS. Finally, flood frequency analysis using the existing method was carried out for comparison and hydrologic impact assessment.

The depth-area-duration curves produced were converted to areal-reduction factors for comparison with Technical Paper No. 40 and No. 49 by the U.S. Weather Bureau. The updated areal-reduction factors were found to be substantially lower in this study than the areal-reduction factors presented in the Technical Papers. This work also examines the factors contributing to the lower areal-reduction factors.

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Chapter 1

Introduction

Engineering design of large hydrologic or hydraulic structures such as dams and levees requires careful analysis of flood frequency so that they may withstand rare, large hydrometeorological or hydrologic events. For example, to design a dam against 100-year floods, one may develop a 100-year design storm based on depth-area-duration (DAD) analysis and input into a hydrologic model to estimate the peak flow from the design precipitation event (Chow et al. 1988). The depth-area-duration curve of a precipitation event relates the volume of rainfall for that storm with the depth of rainfall at a given area for a specified amount of time. Areal reduction factors (ARF) are developed from the DAD relationships by determining mean rainfall over a given storm area as a fraction of the peak rainfall at a point. Further explanation of DAD and ARF relationships are in Chapter 4. While the general concepts and developments put forth in this thesis apply to all forms of precipitation, the study areas are limited to eastern and southern Texas. As such, the terms precipitation and rainfall are used interchangeably throughout this thesis.

Estimating the frequency of extreme precipitation is an inexact science. Rainfall records date back as far as the late 1800s but they are often sparse and inconsistent. It wasn't until the 1940s when rigorous studies of extreme precipitation began. The U.S. Weather Bureau (now the National Weather Service) and the U.S. Army Corps of Engineers (USACE) both began conducting detailed storm studies around that time. From these efforts we now have extreme storm databases, technical papers detailing frequency rainfall events, and probable maximum precipitation (PMP) procedures.

Most of these studies were completed by the 1970s and were not updated until 2004 when the National Oceanic and Atmospheric Administration (NOAA) began conducting and updating what are referred to as the NOAA Atlas 14 studies. For the state of Texas, however, the NOAA Atlas 14 studies have not been initiated. As such, the governing precipitation documents that are currently available include: Technical Paper 40 (Hershfield 1961), Technical Paper 49 (Miller 1964), Tech Memo HYDRO-35 (Frederick et al.1977), Hydrometeorological Report 51 (Schreiner and Riedel 1978) and Hydrometeorological Report 52 (Hansen et al. 1982). These documents concern point rainfall frequency estimation and PMP procedures, but include very little on DAD analysis or guidance for it.

Before the mid-1990s, design storm studies were based solely on rain gauge data. Due to the sparsity of rain gauges, much of the precipitation analysis does not fully capture the spatiotemporal variability of precipitation. Due to the lack of computing power and the amount of calculations and interpolations required, gauge-based depth-area-duration studies are laborious and inherently less objective. Even in areas where there may be a high-density rain gauge network, there is still interpolation between points that may not accurately capture the spatial variability. Not only is rain gauge density a concern, but the time-step by which the data is collected affects the quality of precipitation analysis. Often, a mixture of different time-steps existed in the data in older studies.

Since the mid-1990s the NOAA has been using radar technology in their precipitation estimation operations (see e.g. Seo et al. 2011 and references therein) while archiving the hourly rainfall data since. Being spatially continuous, radar rainfall data can provide more accurate depth-area-duration relationships than rain gauge data. The primary objective of this study is to utilize the radar-based precipitation data in the development of design storms. In this work, the historical Multisensor Precipitation Estimator (MPE, Seo et al. 2011) data are used in DAD and ARF analyses, and the resulting flood frequency analysis is compared with that based on the rain gauge data. The secondary objective of this study is to assess the sensitivity of design storms to precipitation trends observed within the period of record. If the design storms and the resulting flood frequency analysis under precipitation trends are significantly different from those under no trends, it would lend further support to having to account for non-stationarity in flood frequency analysis using, e.g., precipitation projections from climate models. For the above, three catchments in different regions of Texas are used, the Upper Trinity River, the Sulphur River above Patman Lake and the Guadalupe River above Canyon Lake. The U.S. Army Corps of Engineers Fort Worth District has completed three standard frequency design storm studies over the last two years for the above locations. These studies were used in this thesis as a comparison since they were based on rain gauge data.

The radar-based precipitation data used is the MPE data produced operationally by the NWS West Gulf River Forecast Center (WGRFC). The detailed description of the MPE product is beyond the scope of this thesis. The interested reader is referred to Seo et al. (2011) and the references therein. For design storm analysis, the USACE software package HEC-MetVue was used. This newly developed software provided the ability to view radar data and calculate depth-area-duration curves. The same USACE hydrologic models (HEC-HMS) used in the baseline studies were used for this study so that any differences in results may be attributed to the different rainfall data.

Chapter 2

Literature Review

For this study a literature review of technical documents related to extreme precipitation, design storms, and flood frequency analysis was performed. The documents range from the U.S. Weather Bureau's Technical Paper 29 "Rainfall Intensity-Frequency Regime" (Hershfield et al. 1958) to the current, "Flood Frequency Analysis Using Radar Rainfall Fields and Stochastic Storm Transposition" (Wright et al. 2014). This literature review is not meant to provide a complete history of extreme storm precipitation studies; rather it covers the origin of extreme precipitation research by the United States Federal Government, and concludes with a summary of some of the latest research pertinent to this study.

Technical Paper 29 (TP-29) is the first technical paper by the U.S. Weather Bureau that attempted to assess depth-area-duration relationships. With their limited computing resources, however, their method of choice was simply to take the arithmetic mean of station recordings:

> The estimation of areal rainfall with sufficient volume of data to derive general regional duration and frequency relationships could become so laborious as to defeat its purpose. With no precedent for this work, it was necessary to test methods for processing the data. It was found that the drawing of isohyets had no practical advantage over the faster and more objective method of taking the arithmetic mean of sufficient station values to estimate areal depth.

This was a valiant first attempt given the amount of data to be analyzed and computed by the U.S. Weather Bureau. However, the DAD relationships only extend to 400 square miles. This is a significant problem for watersheds of greater than 400 square miles. The final product for depth-area-duration relationships was used in Technical Paper 40 (TP-40) and the same methodology was used for Technical Paper 49 (TP-49). Figure 2-1 shows the final depth-area-duration relationships for Technical Papers 29 and 40.

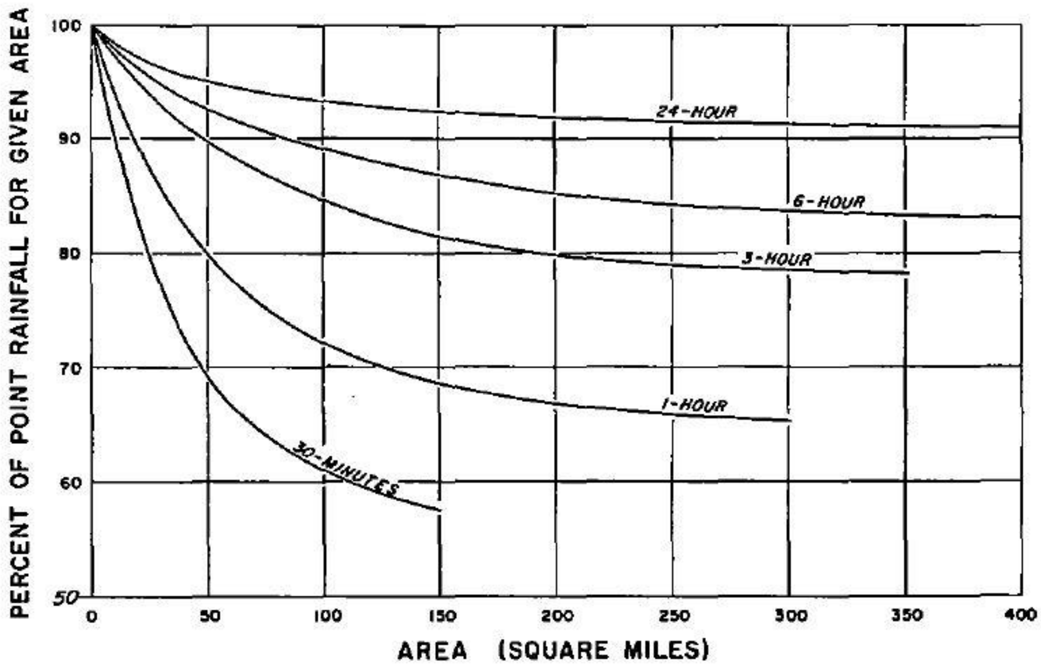


Figure 2-1 The depth-area-duration relationship from Technical Paper 29

Technical Paper 40 titled ""Rainfall Frequency Atlas of the United States for Durations from 30 Minutes to 24 Hours and Return Periods from 1 to 100 Years" (Hershfield 1961), was the first significant rainfall frequency atlas in the United States. In TP-40, statistical stationarity was assumed over the period of record, 1938-1957, to determine frequency rainfall depths. For its time, TP-40 was an excellent resource for hydrologic studies and was used nationwide until NOAA Atlas 14 superseded it in some regions. With the elapse of another 57 years, however, this document is now outdated. Moreover, with the longer period of record available now, statistical stationarity may be checked for appropriateness. Chapter 7 of this study discusses statistical trends in extreme precipitation in Texas and compares the resulting precipitation frequency to TP-40.

Technical Paper 49 titled “Two- to Ten-Day Precipitation for Return Periods of 2 to 100 Years in the Contiguous United States” (Miller 1964) was similar to TP-40 but the analysis was done for longer storm durations. Technical Paper 49 analyzed 370 rain gauges nationwide compared to only 200 in TP- 29 and TP-40. The first 94 rain gauges had a longer period of record, 1912-1961, and the other 276 had a period of record of 1942-1961. While an improvement, TP-49 is still 50 years old and used the crude DAD calculation methods in TP-29.

In TP-29, the sparse rain gauge data were used to identify DAD relationships for storm durations of two to ten days. Again, the DAD curves only extended to 400 square miles where were effectively flat by that point. This presents a problem to watersheds larger than 400 square miles as the areal reduction factor at 1,000 square miles is not likely to be the same as that at 400 square miles. According to TP-49’s Figure 10, however, the areal reduction factor for 400 and 1,000 square miles could be the same or very similar depending on the extrapolation method used.

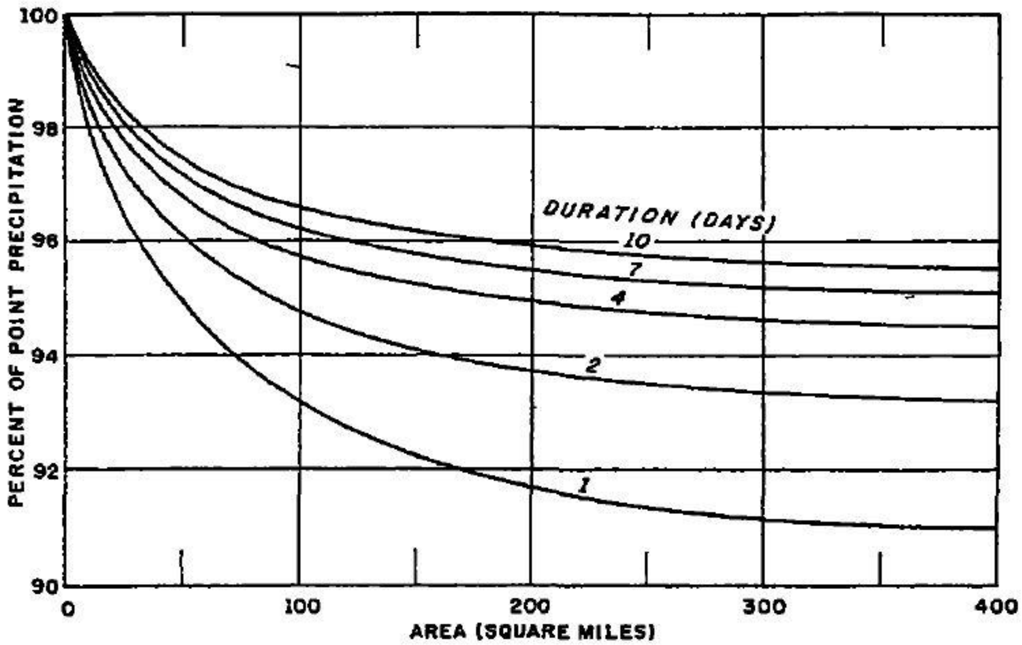


Figure 2-2 The depth-area-duration relationships from Technical Paper 49

The National Weather Service completed a series of Hydrometeorologic Reports for estimation of probable maximum precipitation (PMP). While these studies are not directly applicable to this study, some aspects, such as frequency rainfall, depth-area-duration relationships, storm placement, storm orientation, and storm transposition are helpful.

Hydrometeorologic Report No. 52 entitled "Application of Probable Maximum Precipitation Estimates – United States East of the 105th Meridian" (Hansen et al. 1982) is the standard PMP study used by the USACE Fort Worth District. The study defines the temporal distribution, and isohyetal pattern, orientation, and values for PMP. The temporal distribution and isohyet values are not applicable to this study since the PMP is much larger than the extreme precipitation covered in this study (10-100 year return period).

The isohyetal pattern and orientation from Hydrometeorological Report No. 52 (HMR-52) is of direct relevance to this study. The storm shape of a 2.5 to 1 ellipse on page 20 of the HMR-52 is used in the baseline studies by the USACE and in this study as well. The isohyet orientation described in Chapter 3 of Hydrometeorologic Report No. 52 is also used in the baseline studies performed by the USACE as well as in this study. While HMR-52 is outdated, it is very likely that preferred storm orientations and wind patterns still largely hold.

Hydrometeorological Report No. 51 (HMR-51) is entitled "Probable Maximum Precipitation Estimates, United States East of the 105th Meridian" (Schreiner and Riedel 1978). Detailed in HMR-51 is the process of developing a PMP event, defining envelope curves, maximizing moisture content, etc. HMR-51 is not applicable to this study since it is all related to precipitation events much more extreme than the 10-100 year return period events used in this study. However, pages 10 and 11 in Chapter 2 of Hydrometeorologic Report No. 52 (Schreiner and Riedel 1982) provide rare guidance on the topic of storm transposition. The guidelines provided by HMR-51 are as follows:

> Transposition was not permitted across the generalized Appalachian Mountain ridge.
> Tropical storm rainfall centers were not transposed farther away from nor closer to the coast without additional adjustment.
> In regions of large elevation differences, transpositions were restricted to a narrow elevation band (usually within 1000 ft of the elevation of the storm center).
> Eastward limits to transposition of storms located in Central United States were the first major western upslopes of the Appalachians.
> Westward transposition limits of storms located in Central United States were related to elevation. This varied from storm-to-storm but in most cases the 3000- or 4000-ft contour.
> Southern limits to transposition were generally not defined since other storms located farther south usually provided higher rainfall values.
> Northward limits were not defined if they extended beyond the Canadian border.

While the focus of this study was not on storm transposition, practical guidelines were needed in this study in delineating the storm transposition boundaries, for which HMR-51 proved helpful. The storm transposition guidelines quoted in the previous paragraph were similar to those detailed in Chapter 4 of this study.

In 2012, the consulting firm, Applied Weather Associates performed a study entitled "Site-Specific PMP for North Texas: Bringing HMR-51 into the 21^{st} Century" (Kappel et al. 2012). As with HMR-51, the study was mostly not applicable to this study due to the differences in the nature of the storms at study. However, there were some guidelines about storm transpositioning in the study:

> It was determined from this analysis that storms should not be transpositioned more than +/- 1000 feet in elevation from the original storm elevation and/or +/- six degrees in latitude.

These guidelines were the primary storm transposition rules used in this study. The storm transposition boundaries in this study were based on the quoted guidelines with two exceptions as detailed in Chapter 4.

The Texas Department of Transportation (TxDOT) funded a study entitled "Estimation of Average Rainfall Areal Reduction Factors in Texas using NEXRAD Data" (Olivera et al. 2008). Olivera cited on-going development of next generation radar (NEXRAD) data as the reason to limit the rainfall events in Texas to 2003-2004. Seasonality and regional variations were taken into account in Olivera's study as they compared summer storms and winter storms to see if there was a seasonal effect on the ARF curves. They also broke the state into 6 regions and checked for regional differences in the ARF curves.

As shown in Appendix C, the ARF curves produced in Olivera's study were lower than the ARF curves produced in this study. However, this is an apples-to-oranges comparison for the following reasons. First, due to Olivera's shorter period of record, there were much fewer extreme storms than were examined in this study. Second, Olivera's study only analyzed storms to approximately 400 square miles, per TP29, TP-40, and TP-49. This study, on the other hand, examined extreme storms up to 10,000 square miles.

The Olivera study was a strong indication that the ARF curves may be much lower than those reported in TP-29, TP-40, and TP-49. While this study differs from Olivera's for the reasons cited above, the fact both studies which are based on NEXRAD data instead of rain-gauge data yielded qualitatively similar ARF curves is noteworthy.

A study led by Kenneth Kunkel entitled "Monitoring and Understanding Trends in Extreme Storms" (Kunkel et al. 2013) discusses the state of knowledge of extreme storms. The paper reviews different types of extreme storms and how each type is monitored. Of particular interest, the study reviews the data provided by the National Weather Service's Cooperative Observer (COOP) network across the contiguous United States. By using different generalized extreme value models, Kunkel et al. (2013) tested for trends in extreme precipitation.

The study found that there was a positive trend in extreme precipitation for the southern Great Plains which includes Texas. Kunkel et al. (2013) found that there has been an increase in water vapor which could result in an increase in precipitable water. By three different metrics the extreme precipitation in the southern Great Plains was determined to be increasing.

This study followed Kunkel et al. (2013) in analyzing the NWS COOP network data as detailed in Chapter 7. A positive trend in extreme precipitation, specifically for Texas, was also found in this study. However, this study showed a decrease in storm volumes since 1996, when the NEXRAD data became available. Note that the increase in extreme precipitation is for point rainfall, and not for storm volume.

Wright et al. (2014), in their paper entitled “Flood Frequency Analysis Using Radar Rainfall Fields and Stochastic Storm Transposition”, used stochastic storm transposition (SST) and high resolution NEXRAD data to estimate flood frequency. Wright et al. (2014) studied 4 small, heavily urbanized watersheds in Charlotte, North Carolina, varying in size from 2.5 square miles to 42 square miles. The NEXRAD precipitation data from 2001 to 2010 was used to build storm events for SST for each of the 4 watersheds. The flood frequency analysis included comparisons between tropical storm floods and non-tropical storm floods.

One large difference between this study and Wright et al. (2014) is the catchment size. While Wright’s catchments are all less than 50 square miles, the catchments in this study are all greater than 1,000 square miles. The catchments used in this study are also considerably less urbanized than the catchments used in Wright’s study.

Wright et al. (2014) suggests that the typical design storm approach in flood frequency analysis is flawed due to the limited correlation between rainfall and peak discharge return period. The use of SST accounts for the variability in rainfall intensity, spatial-variability and duration, and theoretically provides a better description between rainfall and peak discharge return period. However, the initial soil moisture in Wright’s study is not varied which reduces the quality of the relationship between rainfall and peak discharge return period. While this study uses design storms and not SST, multiple sets of simulations were made in order to vary the rainfall volume and the initial soil moisture conditions.

Wright et al. (2014) compared design storms to the random storms contained in the SST procedure and found similarity in the design storm flood hydrograph and the SST hydrographs when tropical storms were included in SST. Standard design storm methods do not factor in the spatial and temporal variability that occurs in reality because the ARF curves used are often old and based on storms that are not appropriate for the watershed being studied. This study takes into account the spatial variability by using extreme storms that are transposable to the watershed in determining the ARF curve.

Chapter 3

Design Storm Process

The general approach taken to develop design storms in this work is as follows:

1. The existing design storm and flood frequency analysis by the USACE Fort Worth for the three study basins were used as a reference,
2. Extreme precipitation events were identified within the period of record of the historical MPE data (1996-2013),
3. Storm transposition boundaries were set for each study catchment for the regionalization of extreme precipitation events identified,
4. For each extreme storm assigned to each study catchment, the DAD relationship was analyzed using HEC-MetVue,
5. For each study catchment, a regional ARF curve was developed based on the DAD relationship,
6. Design storms were constructed with the aid of the MPE data using the return period-specific point precipitation depths used in the existing analysis,
7. For each return period, the design storm was simulated in the hydrologic model to calculate and record the hydrograph and peak flow,
8. The flood frequency curve was constructed based on Step 7 for all return periods, and
9. The flood frequency curve from Step 8 was compared with the existing design storm based flood frequency curve based solely on rain gauge data.

Since the period of record of the MPE data is 17 years, two years less than the period of record of TP-40, the record is only beginning to become long enough to have statistical significance. In this study, we used the idea of trading space for time (i.e. borrow storms to your catchment of interest that occurred in the region of similar hydroclimatology) from SST to effectively lengthen our period of record. For each study basin, a set of storm transposition boundaries were set and all the extreme storms within these bounds were used to determine the appropriate regional ARF curve.

As mentioned in Chapter 1, the second objective of this thesis was to assess the sensitivity of design storms to precipitation trends observed within the period of record of MPE data. In order to assess possible precipitation trends, the following approach was taken:

1. The existing USACE design storms were simulated in their respective hydrologic models with dry and wet initial soil moisture conditions,
2. The maximum envelope ARF curve for each study basin was used to develop design storms,
3. The maximum envelope ARF curve design storms were simulated in the hydrologic model, and
4. The additional hydrologic simulations were incorporated in the flood frequency analysis.

To analyze rainfall and calculate the DAD relationships, the USACE rainfall analysis tool, HEC-MetVue was used. HEC-MetVue allows for the visualization, editing, and analysis of MPE data. Design storms were created using basic scripting and HEC-MetVue was used to calculate the basin average precipitation for the hydrologic models. From the baseline studies by the USACE, the HEC-HMS models were used to calculate the peak discharge and inflow hydrographs. These models were used again in this study with the MPE data-based design storms. Finally, the USACE statistical software, HEC-SSP was used for the flood frequency analysis.

As introduced in Chapter 1, the three watersheds used in this study include the Upper Trinity River Basin that drains to the Trinity River at Dallas (http://water.weather.gov/ahps2/hydrograph.php?wfo=FWD&gauge=DALT2), the Sulphur River Basin that drains to Wright Patman Dam, and the Guadalupe River Basin that drains to Canyon Dam. The Upper Trinity River is located in North Central Texas and runs through the Dallas-Fort Worth Metropolitan Area. This heavily urbanized watershed has a total drainage area of 6,100 square miles (see Figure 3-2) with an uncontrolled catchment area of 1,100 square miles and an average annual rainfall of 35 inches. The Sulphur River watershed is located in the Northeast corner of Texas, has a drainage area of 3,400 square miles, and an average annual rainfall of 40 inches. The watershed of the Guadalupe River above Canyon Dam is 1,400 square miles and has much steeper slopes than the first two basins. This catchment is located in South Central Texas hill country and has an average annual rainfall of 30-35 inches. The 4 figures below show the study basins and a table with their TP-40 and TP-49 point rainfall depths.

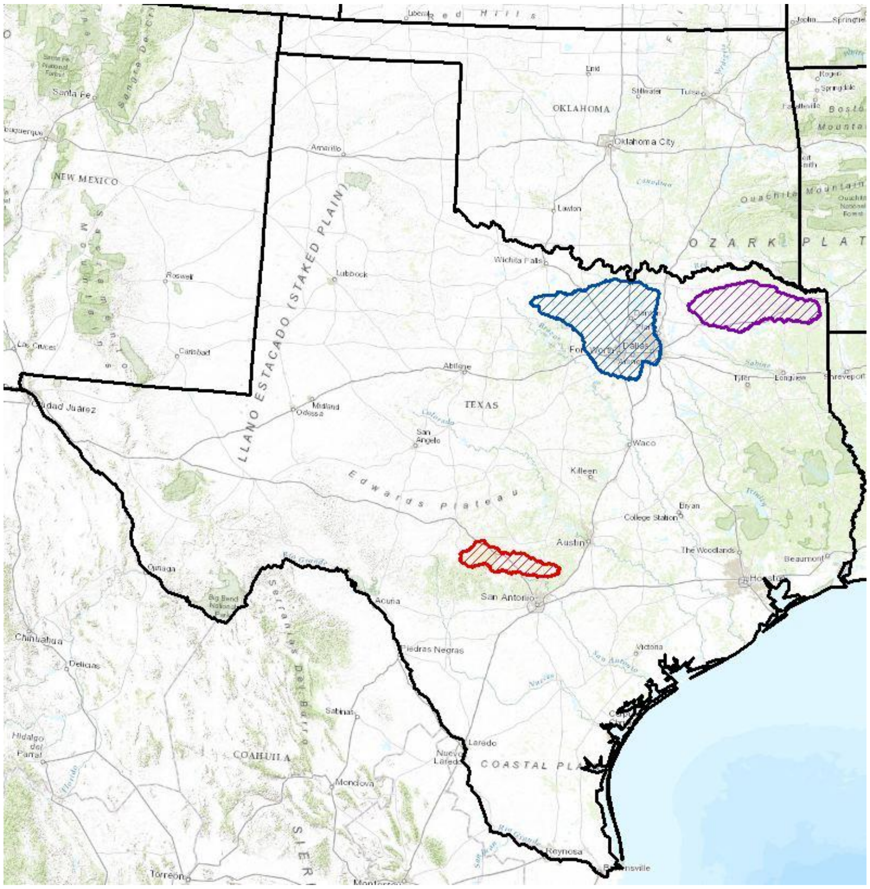


Figure 3-1 Study basin map

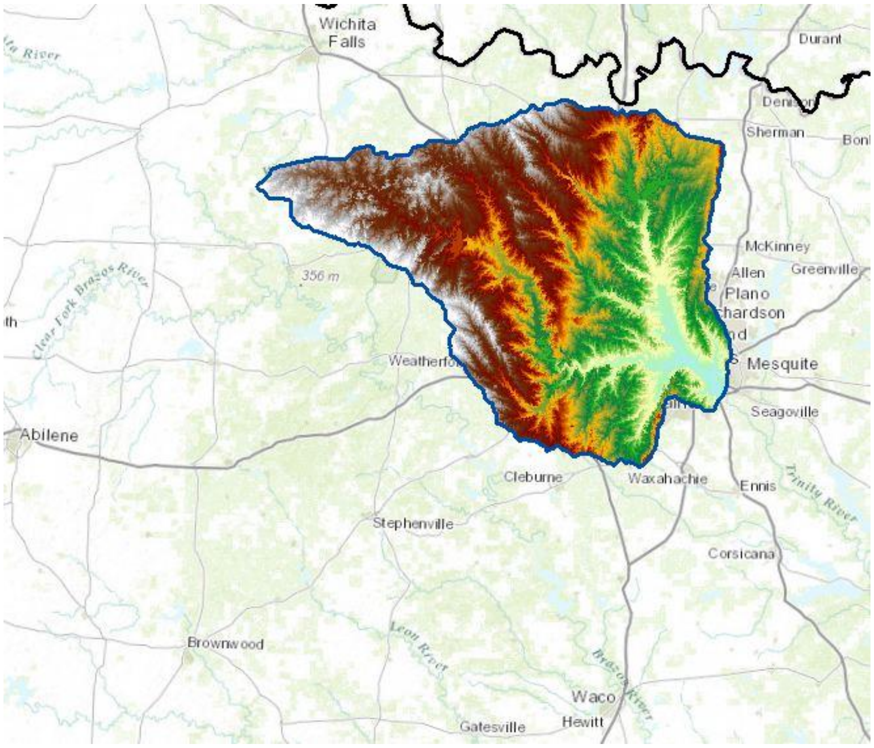


Figure 3-2 Upper Trinity River basin map

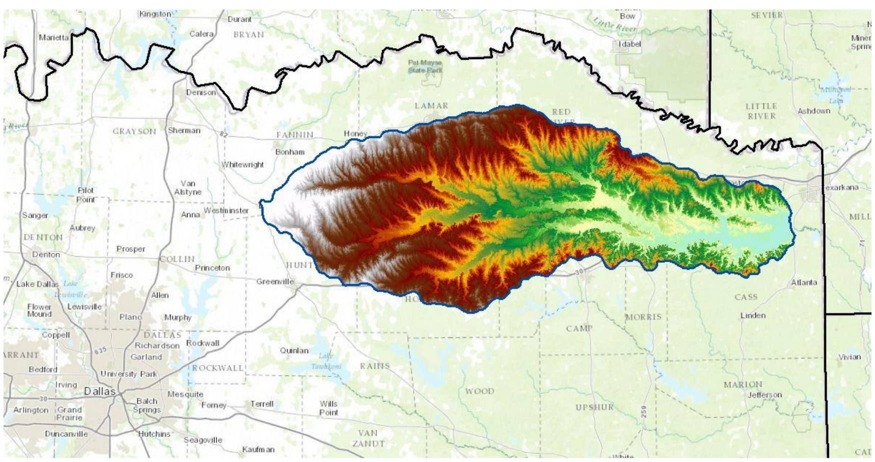


Figure 3-3 Sulphur River basin map

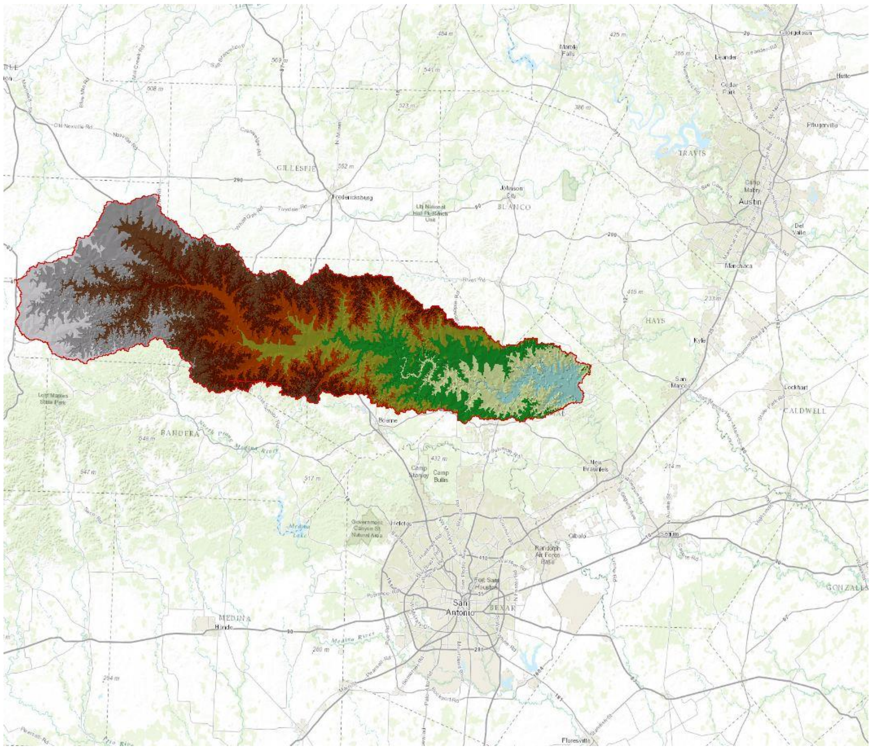


Figure 3-4 Guadalupe River basin map

Table 3-1 Study basins and their point precipitation frequency

Upper Trinity River		**Sulphur River**		**Guadalupe River**	
Drainage Area	1,100 sq. mi.	Drainage Area	3,400 sq. mi.	Drainage Area	1400 sq. mi.
Return Period	**24 Hour**	**Return Period**	**96 Hour**	**Return Period**	**24 Hour**
2-YR	4.0	2-YR	5.8	2-YR	4.0
5-YR	5.4	5-YR	7.6	5-YR	5.5
10-YR	6.4	10-YR	8.8	10-YR	6.6
25-YR	7.5	25-YR	10.6	25-YR	7.9
50-YR	8.6	50-YR	11.9	50-YR	8.9
100-YR	9.6	100-YR	13.3	100-YR	10.0

Chapter 4

Design Storm Analysis

The creation of a synthetic design storm is a lengthy and involved process. Design storms are a synthetic idealized representation of a storm of a certain return period for a given region. Design storms are typically used in the design of infrastructure, determining flood plains, and flood frequency analysis. While widely assumed as such in practice, in reality a design storm with a given return period does not solely determine the peak discharge of the same return period due to other hydrologic and hydrometeorological factors such as varying initial soil moisture conditions and varying storm durations. In this study, the above assumption is alleviated by varying the initial soil moisture conditions in the hydrologic models.

Before the creation of a design storm can occur, site-specific parameters must be set. The driving factor in the process is the storm location over the watershed. The hydroclimatology specific to the location of the watershed affects the duration, temporal distribution, point rainfall depth, and spatial variation of the storms. All these parameters must be decided before the synthetic design storm can be created.

In creating design storms for this study, the same process that the USACE used was followed and their information was used with the exception of the spatial variability. The USACE had already determined the critical storm location, point rainfalls based on TP-40, storm duration, temporal distribution, and storm shape for each study basin. Therefore, the only thing that was changed was the spatial variability i.e. the areal reduction factors used.

The difference between the gauge- and MPE-based areal reduction factors is due not only to the difference in rainfall data type but also to the difference in the period of record of the datasets used. The USACE developed their depth-area curves based on extreme storms from 1894 through 2008 and used rain gauge networks to calculate the depth-area curves. This study took extreme storms from 1996 through 2013 and calculated the depth-area curves based on the MPE data. Areal reduction factors are calculated per storm, using the depth-area curve.

The storm locations determined by the USACE were developed to maximize the discharge at the study location; either a lake inflow or a stream-flow gauge. The storm durations were determined by the USACE based on the response time of the watersheds. The point rainfalls at different return periods were calculated by the USACE based on TP-40 and the storm shape was taken from HMR-52, a 2.5 to 1 ellipse. The temporal distribution or synthetic storm hyetograph used by the USACE was a form of alternating block method either derived from HMR-52 for storm durations of 96 hours or from the standard hyetograph built into HEC-HMS for the 24 hour storm. The storm hyetograph information can be found in Appendix B.

Once the design storm is created, HEC-MetVue calculates the mean areal precipitation over the watershed sub-basins for use in the semi-distributed, hydrologic model (HEC-HMS). The HEC-HMS model then calculates the runoff from the design storm and the results are compared to the baseline studies.

The storm database used in this study was collected from multiple sources and focused on the southern states of Texas, Oklahoma, Arkansas and Louisiana. The National Climactic Data Center (NCDC) catalogs extreme weather events, the USGS keeps annual statistics on their streamflow gauges, and the USACE keeps a record of lake inflows and elevations. All these data were combined, categorized and formed into a database of dates for which the MPE data were visually inspected using HEC-MetVue. All storms with a point rainfall of five inches or more within a 24 hour period were recorded in a database (the final storm database recorded is given in Appendix A).

While the period of record of MPE data is shorter than ideal, by trading space for time, the period of record may effectively be lengthened. In order to determine the typical characteristics of a rainfall event for a certain study site, the limits of storm transposition to that site must be defined. Storm transposition boundaries are based on the study site's climate and regional storm records. Once these boundaries are set, the storms in the storm database that fall within the storm transposition boundaries are used to determine the region's storm characteristics. The storm transposition boundaries are set solely for the purpose of determining what storms within the database could have, theoretically, occurred over the study basin. Hence, by taking the regional extreme storms that theoretically could have occurred over the study basin, we increase the number of extreme storms for the study basin with the same period of record.

The Applied Weather Associates (AWA), a meteorological science consulting company from Colorado did a PMP study and published a paper "Site-Specific PMP for North Texas: Bringing HMR 51 into the 21st Century" (Kappel et al. 2012). This PMP study was performed for four lakes operated by the Tarrant Regional Water District (TWRD). The AWA study included a record of extreme storms that was used to confirm that no storms were excluded from the region of study specific to this thesis.

The Applied Weather Associates PMP study in Texas also provided some guidance on setting storm transposition boundaries. The AWA gave three guidelines for storm transposition: first, storms must not be transposed to an elevation of +/- 1,000 feet from the storm location; second, storms must not be transposed more than +/- 6 degrees of latitude; third, storms within 50 miles of the coastline cannot be transposed. Below is a map of the AWA's storm transposition boundaries.

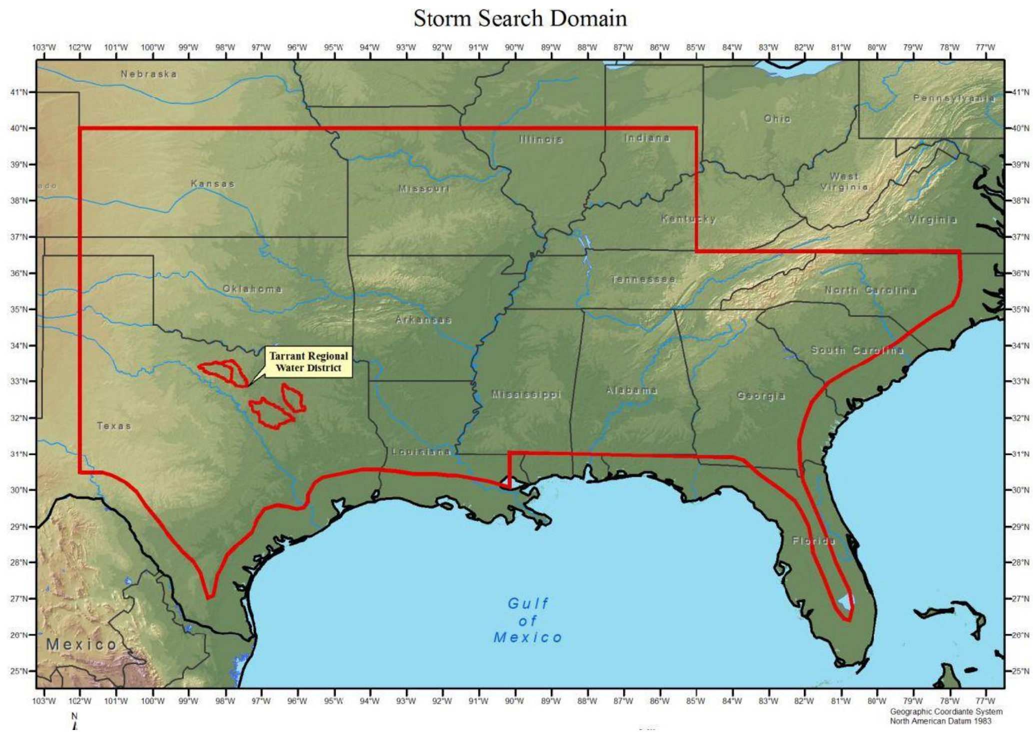


Figure 4-1 The Applied Weather Associates' storm transposition boundaries

The hydrometeorological reports (commonly referred to as HMR) from the NOAA provide similar storm transposition guidelines to the AWA study. The HMR-51 (1978) concurs with the +/- 1,000 foot elevation criterion used by AWA and HMR 55a (1988) has a similar criterion as it uses +/- 1,500 feet in elevation. Hydrometeorological Report 59 (1999), which is for the state of California but is the most recent HMR, does not provide much guidance on storm transposition except to say:

> "The limits to the transposition of a particular storm are somewhat subjective, but essentially reflect the analyst's judgment as to what is meteorologically possible. Generally, storms are not transposed across major ridgelines, a large distance from significant moisture sources, or into different climatic zones."

For this study, the storm transposition criterion set by the AWA study was used with two additional criteria. First, the storms must be no further south than the Texas-

Mexican border; second, the storms must be no further East than the Mississippi River. Below are the three maps showing the site-specific storm transposition boundaries for each watershed and the three figures showing how the storms selected compare to TP-40 values.

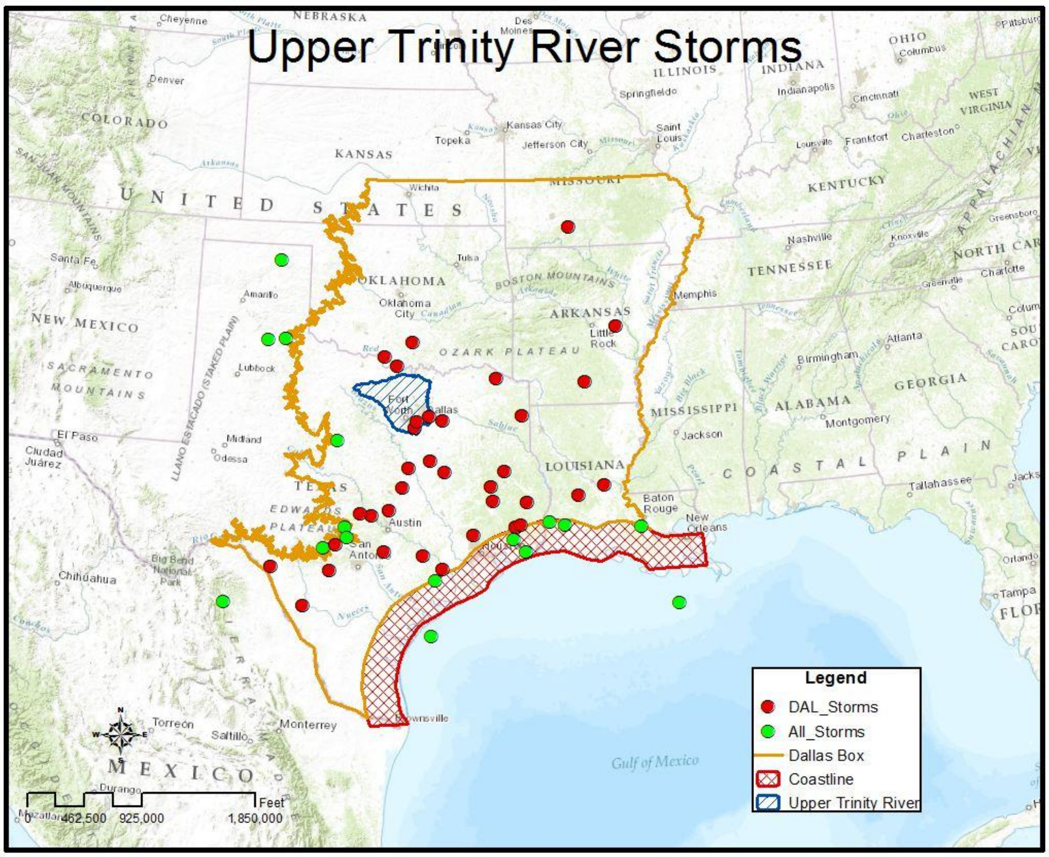


Figure 4-2 Upper Trinity River watershed storm transposition boundaries

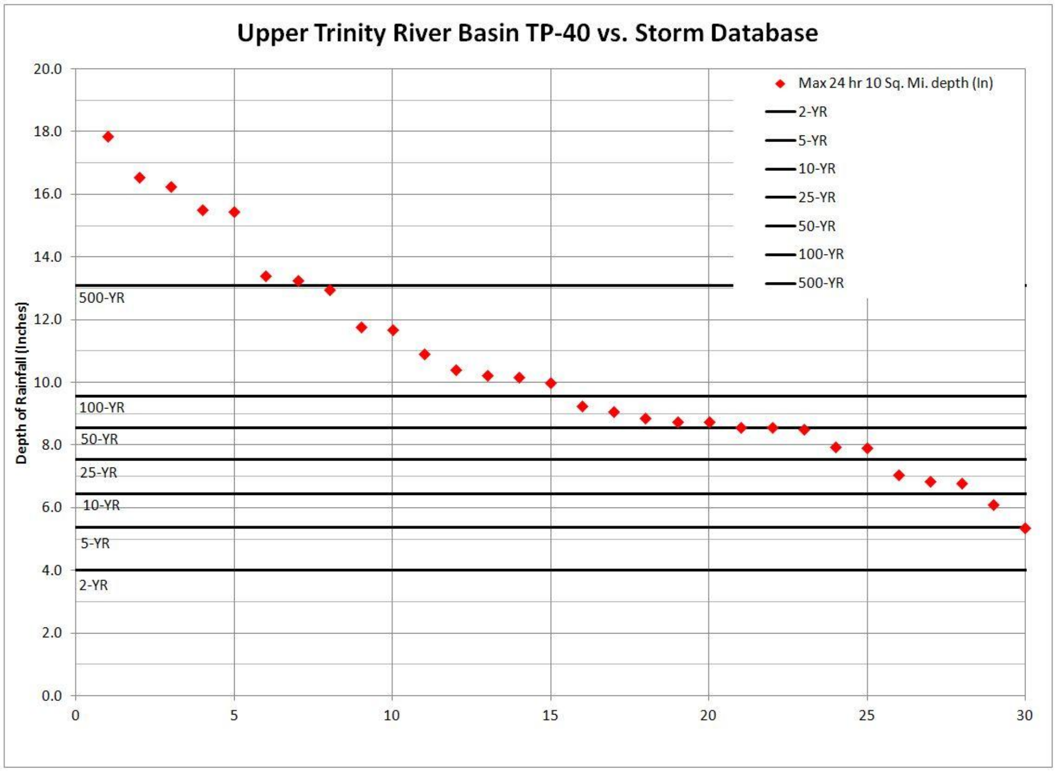


Figure 4-3 Upper Trinity River storm point rainfall summary

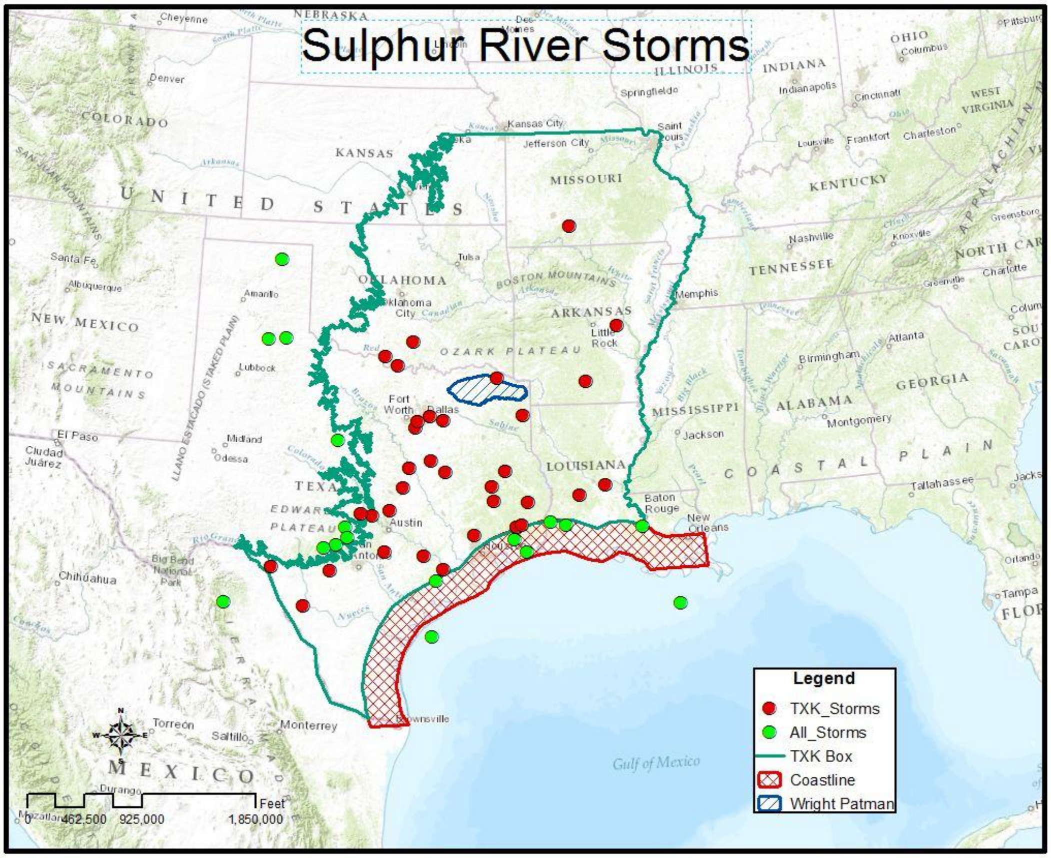


Figure 4-4 Sulphur River watershed storm transposition boundaries

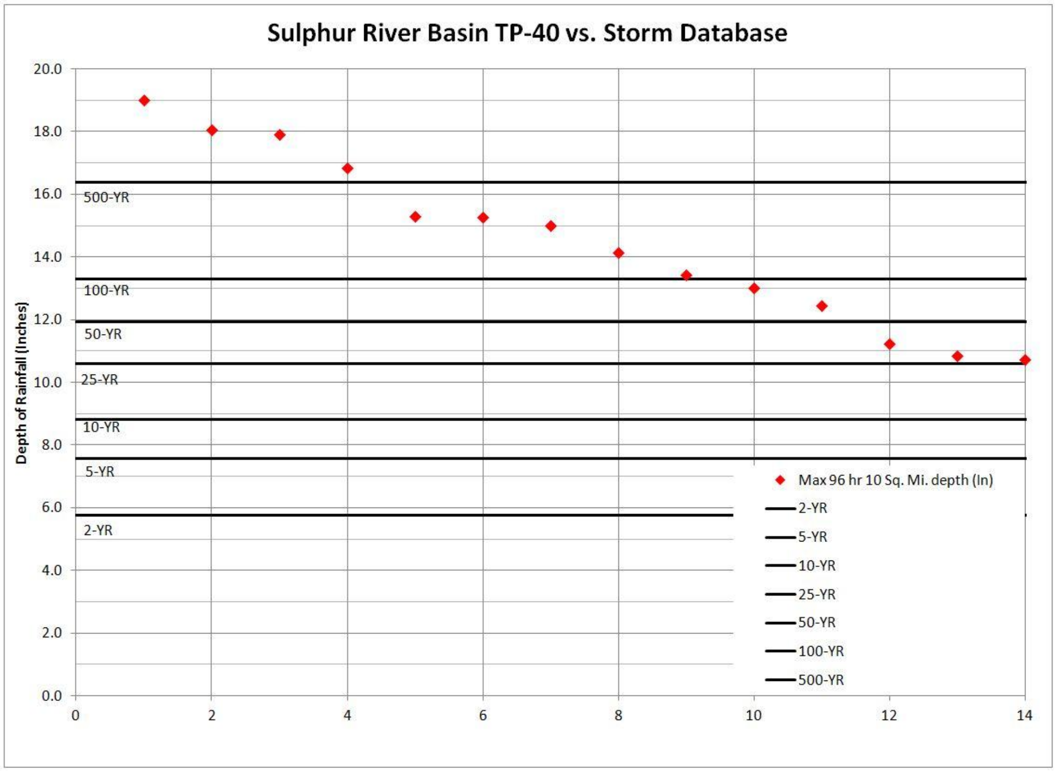


Figure 4-5 Sulphur River point rainfall summary

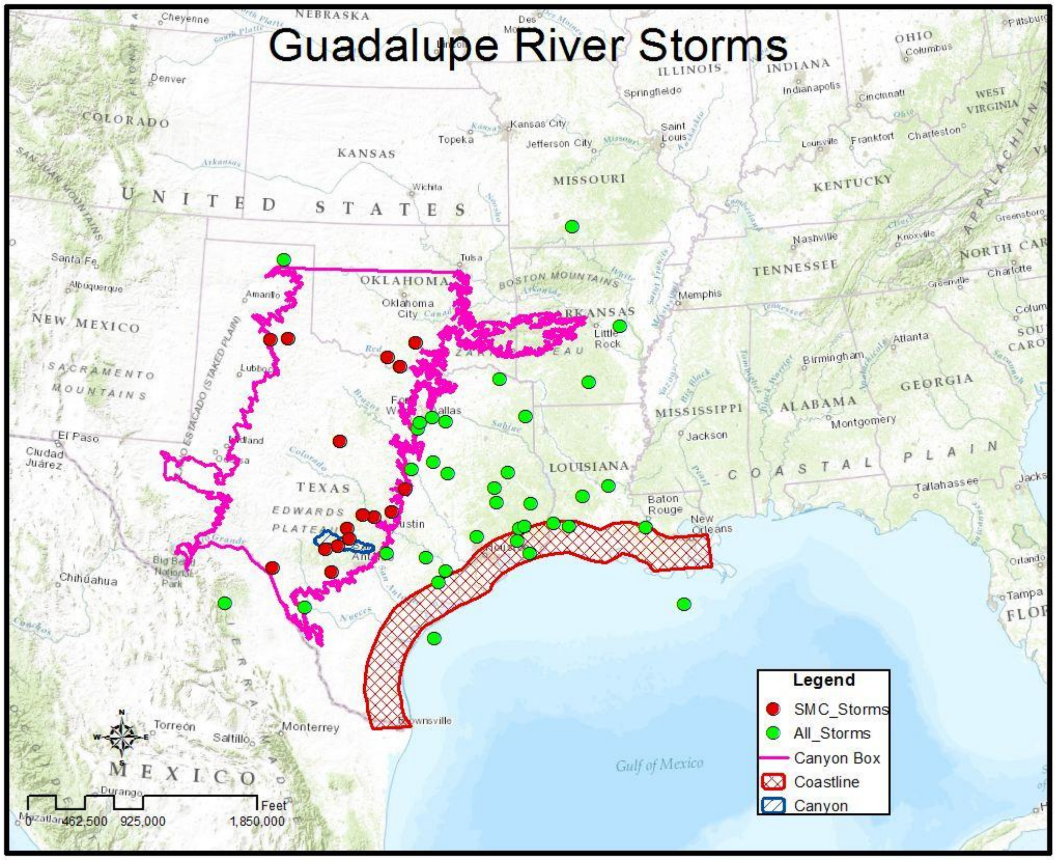


Figure 4-6 Guadalupe River watershed storm transposition boundaries

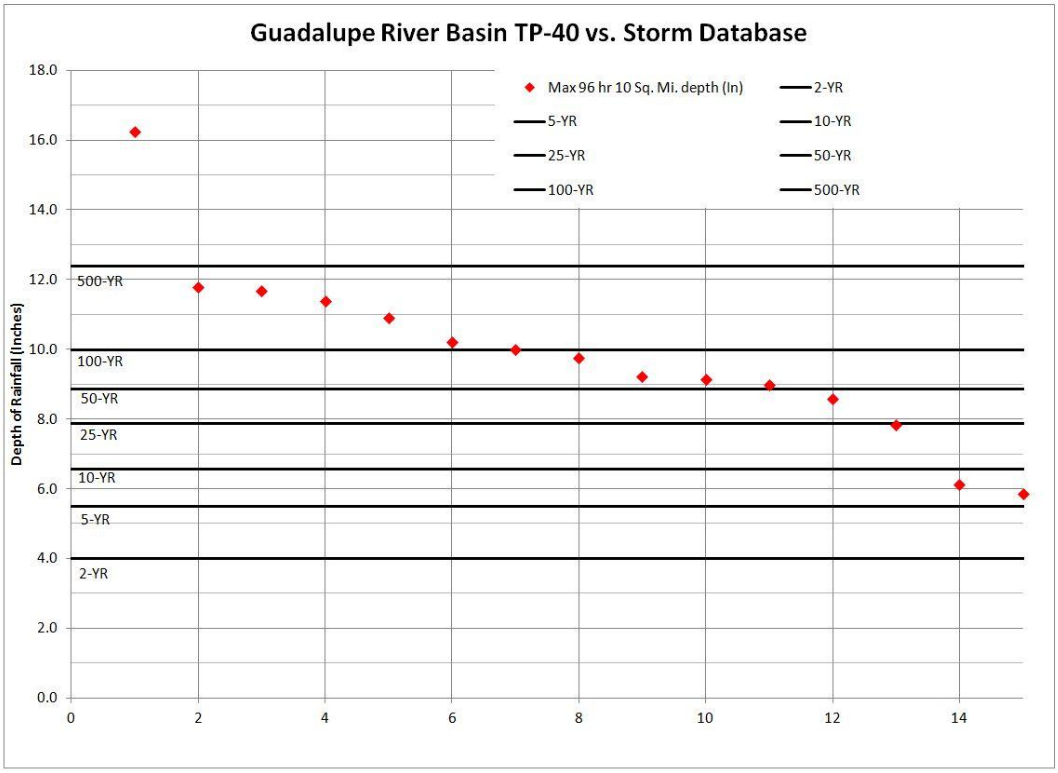


Figure 4-7 Guadalupe River storm point rainfall summary

For each study basin, there was a set of storms in the database that qualified for transposition to the study site. To achieve a normal distribution of storms to be compared to the baseline range of standard frequency events, storms with a point rainfall less than the five year return period were removed from consideration. These storms were considered too minor for the purpose of this study. Additionally, storms with a point rainfall exceeding 20 inches were also removed from consideration. These storms were considered too severe to be compared to standard frequency rainfall events. Using the criteria specified above, there were a total of 30 storms used for the Upper Trinity River, 14 storms for the Sulphur River, and 15 storms for the Guadalupe River.

For each storm in the database, the DAD tables were calculated using HEC-MetVue. Since the design storms for this study were either 24-hours or 96-hours in duration, only these two durations were analyzed. The 24-hour and 96-hour depth-area curves were then converted to ARFs by dividing the depth of rainfall at each given area, by the depth of rainfall at the 10 square-mile area. A best-fit line based on the median data points was applied to each of the ARF curves. This was the same approach taken by the USACE in their studies.

Below are the plots showing the DAD and ARF curves for each dataset. For each ARF plot there is a comparison to previously established ARF curves: the ARF curve in TP-40 (Figure 15), the ARF curve in TP-49 (Figure 10) and the ARF curve used in the USACE studies. The ARF plots also include a maximum and minimum envelope curve to show the range of the variability.

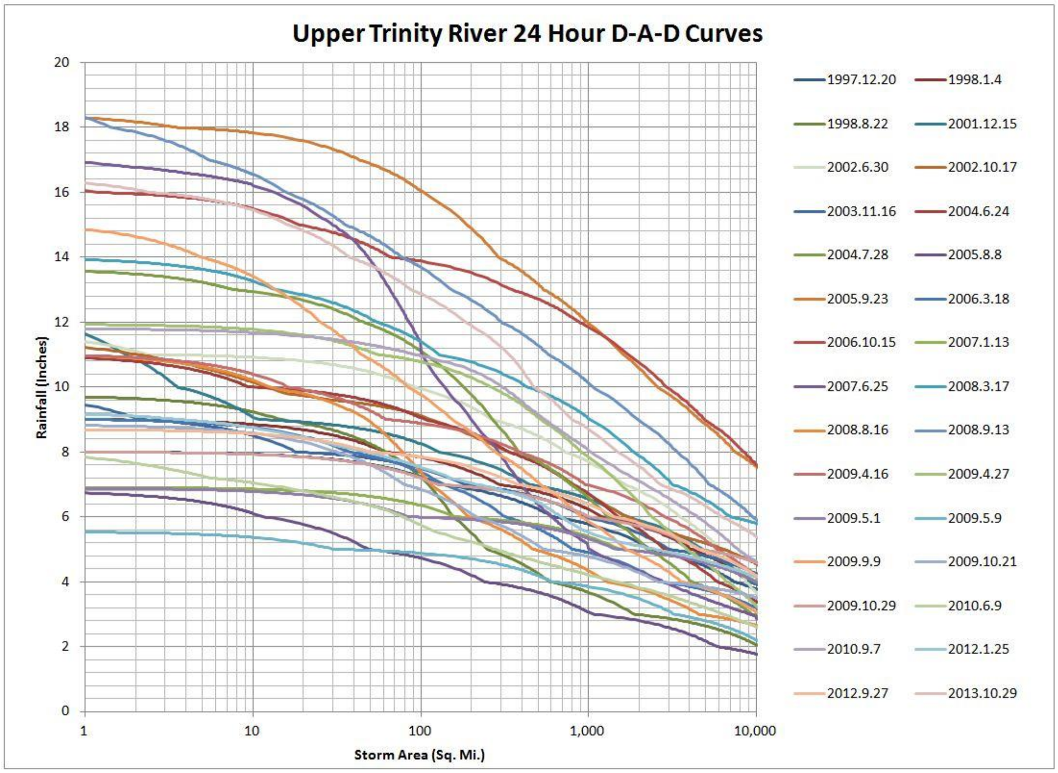


Figure 4-8 Upper Trinity River depth-area-duration curves

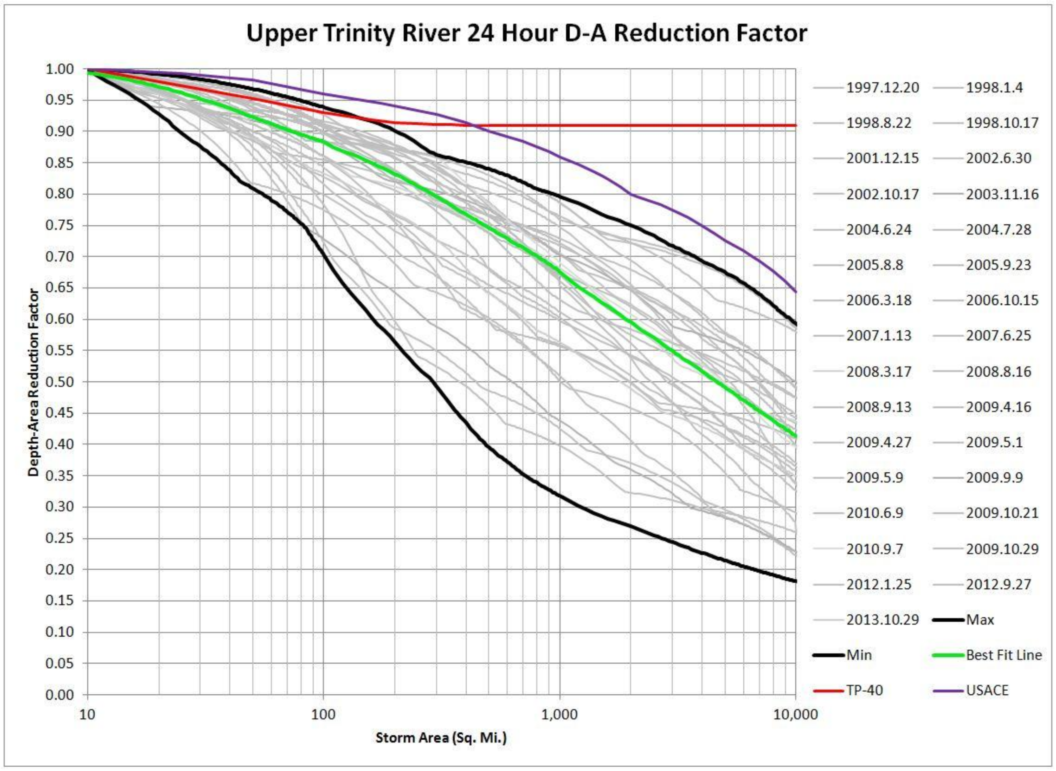


Figure 4-9 Upper Trinity River areal-reduction-factor curves

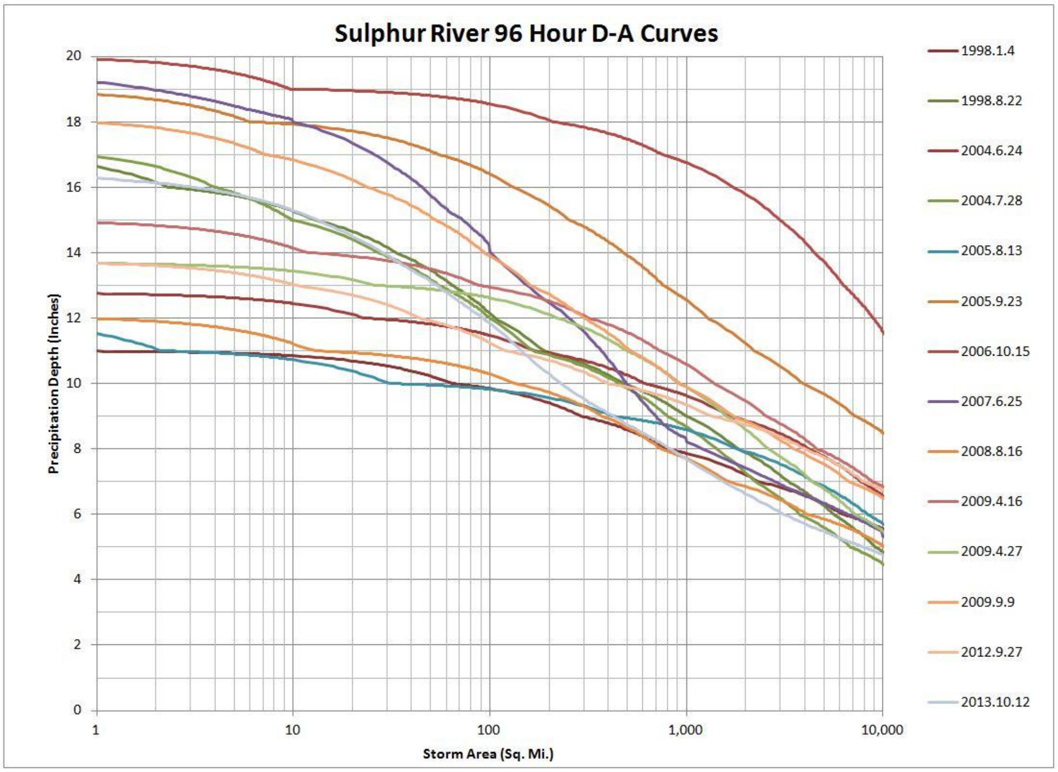


Figure 4-10 Sulphur River depth-area-duration curves

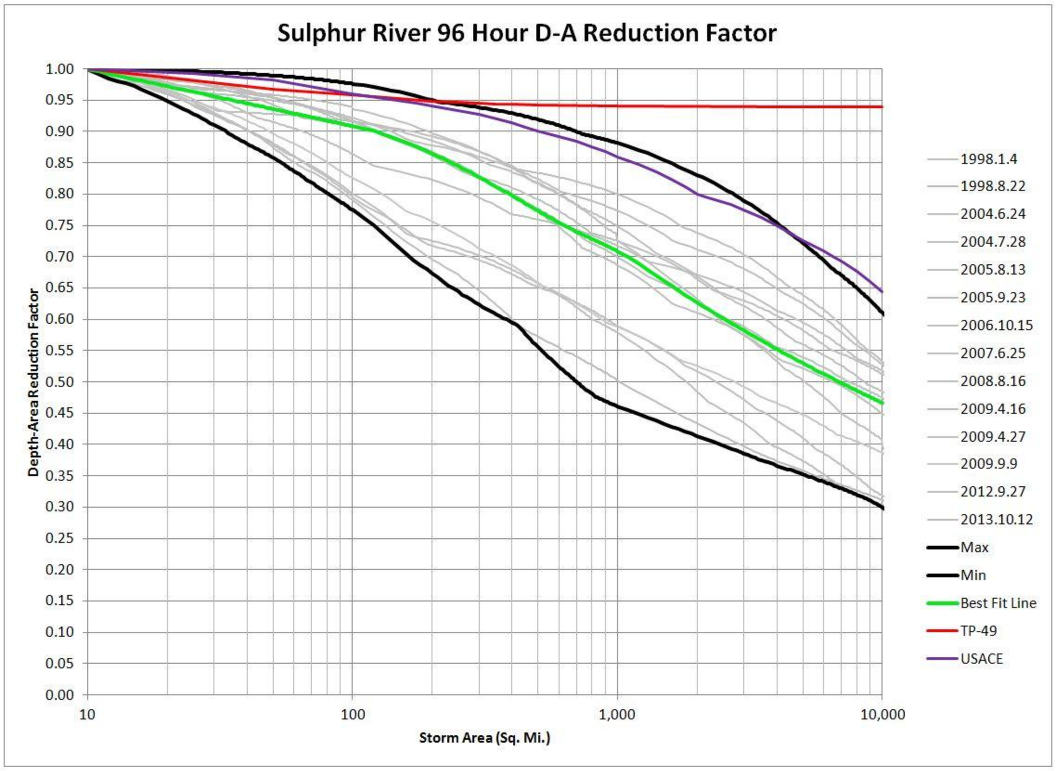


Figure 4-11 Sulphur River areal-reduction-factor curves

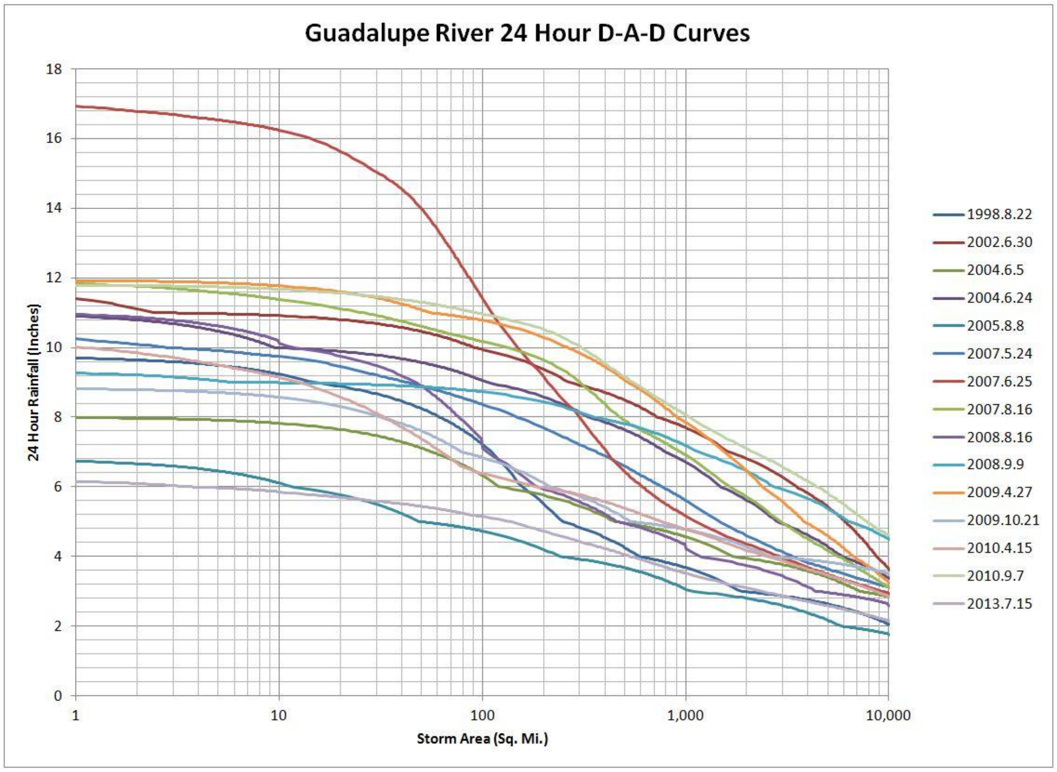


Figure 4-12 Guadalupe River depth-area-duration curves

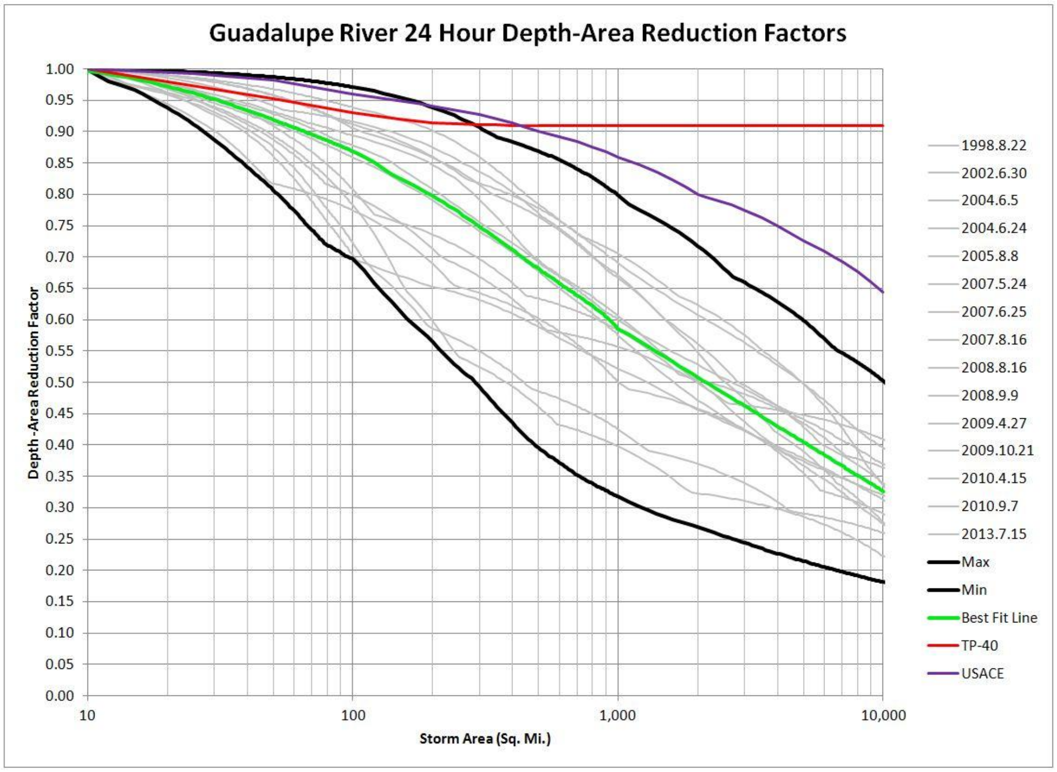


Figure 4-13 Guadalupe River areal-reduction-factor curves

Finally, two 3D plots were produced to demonstrate the difference in rainfall volumes between the USACE baseline study ARF curve and the MPE-based ARF curve for the Upper Trinity River. Figure 4-14 shows the USACE baseline study design storm in 3D and Figure 4-15 shows the median MPE design storm from this study in 3D.

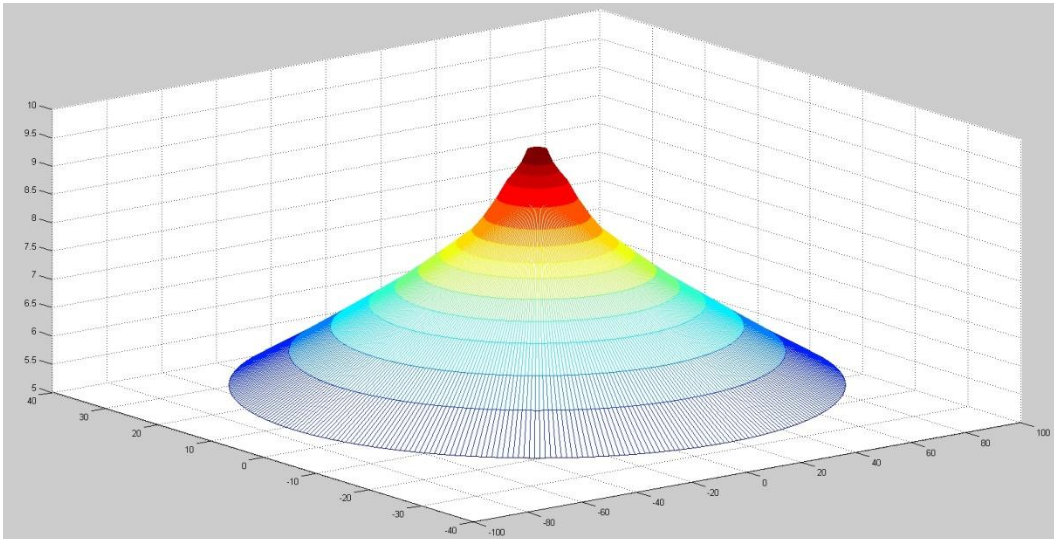


Figure 4-14 A 3-dimensional plot of the USACE design storm for the Upper Trinity River

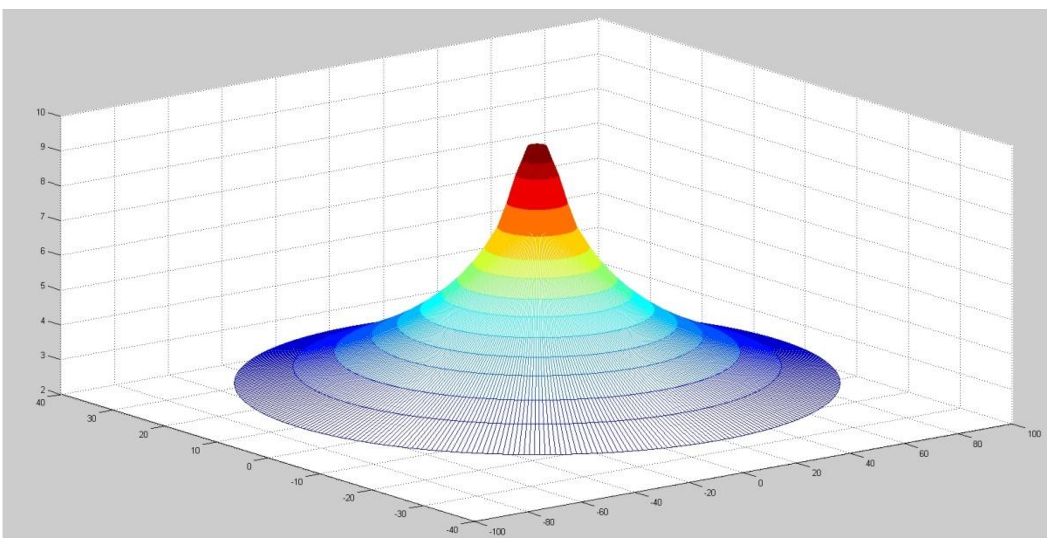


Figure 4-15 A 3-dimensional plot of the updated design storm for the Upper Trinity River

Chapter 5

Hydrologic Modeling

To estimate peak flows associated with the design storms, hydrologic modeling of the study basins is necessary. Because the simulated peak flows effectively serve as substitutes for observed flows, it is important that the quality of hydrologic modeling is as high as possible. Due to various sources of hydrologic and hydraulic uncertainties, however, hydrologic model simulation results are subject to errors (see e.g. Seo et al. 2006, Demargne et al. 2014). This chapter describes the hydrologic modeling and validation results for the three study basins to provide a measure of rigor in modeling and accuracy in the modeling results.

Upper Trinity River Hydrologic Modeling

In 2012, the USACE Fort Worth District updated their hydrologic modeling of the Upper Trinity River using HEC-HMS for a project for the North Central Texas Council of Governments. Design storms were built and simulated in the hydrologic model to determine standard frequency flows at certain flow gauges along the Trinity River. The standard frequency events were considered to be storms with return periods of 2, 5, 10, 25, 50,100 and 500 years. From the 2012 study, the same hydrology model was used to compare flows at the Dallas gauge (USGS 08057000).

The study done in 2012 by the USACE was the update of a previous study: “Upper Trinity River Feasibility Study” (U.S. Army Corps of Engineers, 2012). The “Upper Trinity River Feasibility Study” produced a HEC-1 hydrology model for the purpose of calculating peak discharges within the Upper Trinity River corridor. In the 2012 Corridor Development Certificate study, the HEC-HMS model was initialized based on the previous model and used a one hour time step. The hydrology model covered the headwaters contributing to the Trinity River at Dallas Gauge (USGS 08057000) including the Clear Fork, West Fork, Elm Fork and Main Stem of the Trinity River. The hydrologic methods used in the study were: Snyder's Unit Hydrograph transform method, Initial and Constant Loss method, the Recession baseflow method and a mix of Modified Puls, Muskingum, and Lag routing methods.

The initial abstraction and infiltration rates and baseflow parameters were adopted from the "Upper Trinity River Feasibility Study". The storage routings were updated along with the Snyder's time-to-peak factors and the imperviousness of the catchments according to the U.S. Army Corps of Engineers' analysis of the 2005 land use data provided by the North Central Texas Council of Governments.

In the 1970s the USACE performed storm reproductions for many storms to calibrate the hydrology model, specifically the initial abstraction. From these calibrations, initial abstractions and constant infiltration losses were calculated for the standard frequency return periods comparable to the standard rainfall return periods, e.g. the 100-year soil loss rates. The 100-year loss rates are low loss rates that have a 0.01 probability of occurrence and would produce higher runoff values than the 10-year loss rates with the same rainfall. The loss rates were approved by the North Central Texas Council of Governments and have been used in all the Upper Trinity River Corridor Development Certificate studies since.

In the 1990s, the USACE hydrology model (then HEC-1) for the Upper Trinity River was validated and further calibrated with several different storm events including May-June 1989, April-May 1990, and December 1991 as part of a land-use update study. In 2012, a similar study was done to update the land-use and transition from HEC-1 to HEC-HMS. The 2012 study included the 2005 land-use data and the September 2010 storm event was used for validation.

For the purposes of this study, the Upper Trinity River HEC-HMS model was used for simulations of wet (500 year loss rates), dry (2 year loss rates) and average conditions. These simulations help show the sensitivity of the peak discharge rates to varied initial soil moisture and the range of control that the initial soil moisture has on flood frequency analysis. In addition to these 3 simulations, the updated design storms using the median and maximum envelope ARF curves were simulated with average soil moisture conditions for comparison to the original design storm study. The rationale for considering only the median and maximum ARF curves is explained Appendix D.

The storm centering from the Upper Trinity River study conducted by the USACE was used in this design storm study as well. The storm center and orientation were determined for maximum runoff at the Dallas flow gauge. The storm location and orientation can be seen over the catchment in the figure below.

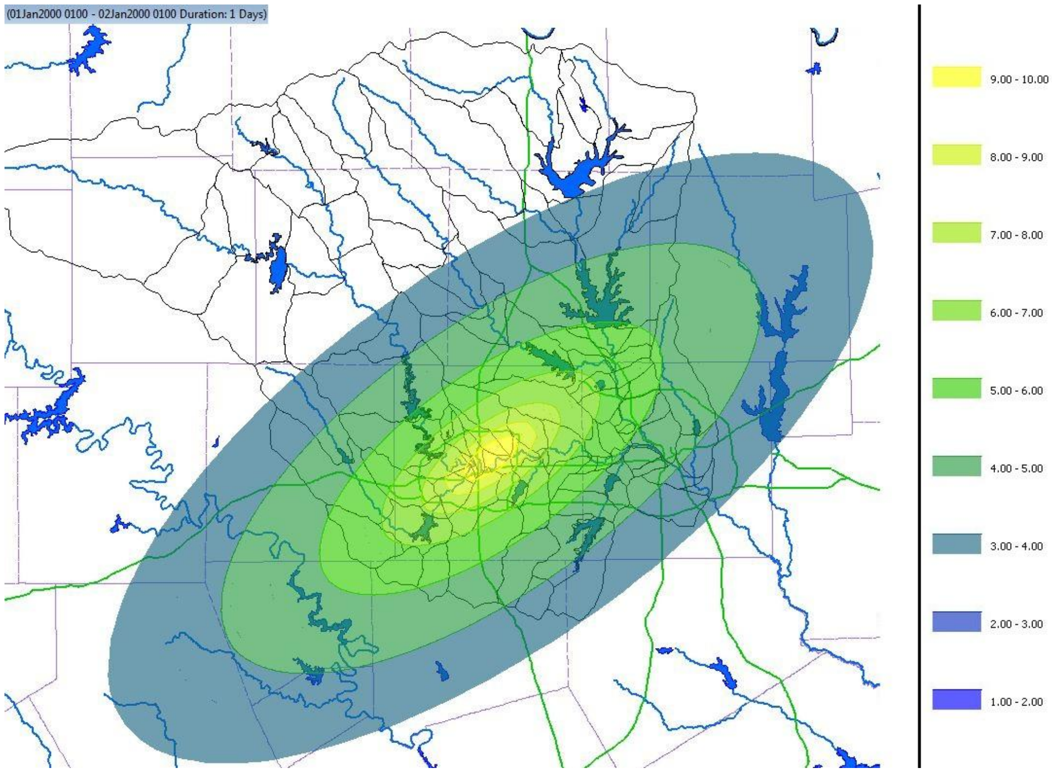


Figure 5-1 Upper Trinity River design storm location and orientation

Sulphur River Hydrologic Modeling

The Sulphur River was studied by the USACE Fort Worth District in 2014 for a periodic assessment of dam safety at Wright Patman Dam (U.S. Army Corps of Engineers, 2014a). The watershed was modeled in HEC-HMS from the headwaters to Wright Patman Dam and used a one-hour time step. The standard frequency design storms and probable maximum precipitation were simulated to find the corresponding Wright Patman Lake inflows and pool elevations.

The hydrology model used the following hydrologic methods: Deficit Constant loss method, Snyder's Unit Hydrograph transform method, Recession baseflow method, and a combination of Muskingum and Modified Puls routing methods. The model was initialized based on similar models that the USACE previously used in flood forecasting. For calibration, the following events were used: March 2001, May 2009, and October 2009. Based on the calibration results, dry, wet, and average conditions were developed. For each sub-catchment, the maximum soil losses were assigned to the “dry” model and the minimum soil-losses were assigned to the “wet” model. Thus, the wet and dry models closely represent the bounds of the initial losses. The average initial losses for each sub-catchment were assigned to an “average” model.

The same HEC-HMS model was used for hydrologic simulations in this study. There were five series of simulations completed, three baseline series using the design storms the USACE developed with wet, average, and dry soil moisture conditions and two series with the MPE-based design storms using the median and maximum envelope ARF curves and average soil moisture conditions. The three baseline conditions were intended to show the sensitivity of the watershed to initial soil moisture compared to the effect of the change in volume of rainfall would have on the lake inflow. A series of simulations included the 10, 25, 50, and 100-year return period design storms.

The storm center and orientation were set in the USACE study to optimize peak inflow into Wright Patman Lake. The same storm center and orientation were adopted for this study. The updated 100-year design storm can be seen in the figure below.

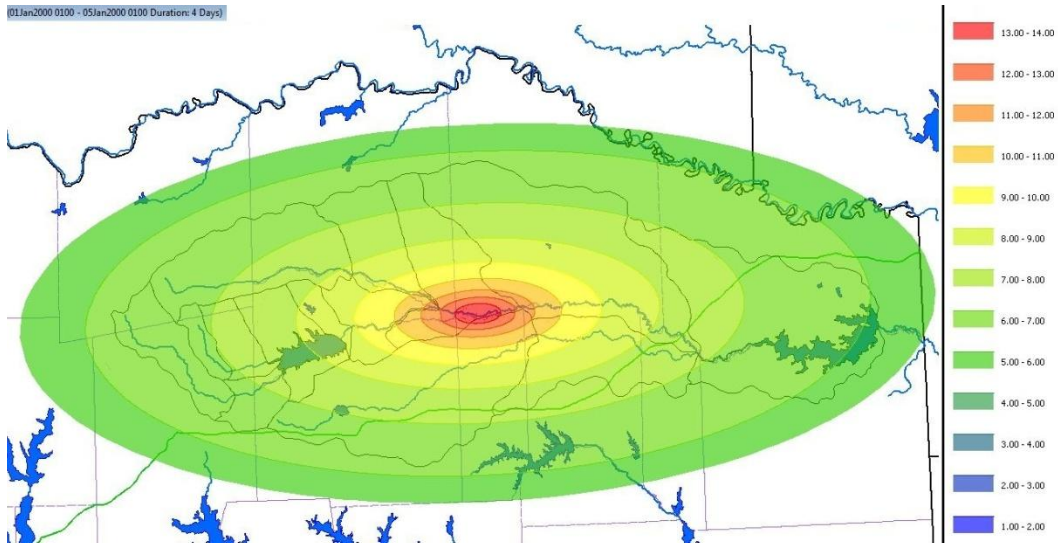


Figure 5-2 Sulphur River design storm location and orientation

Guadalupe River Hydrologic Modeling

The Guadalupe River was studied by the USACE Fort Worth District in 2014 as part of a basin-wide flood forecast model update (U.S. Army Corps of Engineers, 2014b). The entire Guadalupe River, from headwaters to the Gulf of Mexico, was modeled in HEC-HMS. Using this hydrologic model, the standard frequency design storms were simulated to find the corresponding pool elevations at Canyon Dam. This HEC-HMS also used a one-hour time step.

The HEC-HMS model developed in this study used the following hydrologic methods: Deficit Constant loss method, Snyder’s Unit Hydrograph transform method, Recession baseflow method, and a combination of Muskingum and Modified Puls routing methods. The hydrologic parameters were initialized using the U.S. Army Corps of Engineers’ Geospatial Hydrologic Modeling tool, HEC-GeoHMS. The Soil Survey Geographic database (SSURGO) by the National Resources Conservation Survey was used to estimate the initial soil loss parameters. Physical factors such as watershed slopes and longest flow paths were used to estimate the Snyder's Unit Hydrograph parameters and Recession baseflow parameters. Muskingum routing was used above Canyon Dam and the parameters were initialized based on the physical data of the watershed. Modified Puls storage routing was used below Canyon Dam and the storage-discharge relationships were determined by a calibrated HEC-RAS model. However, for the purpose of this study, the flow below Canyon Dam was ignored.

In the calibration process, four storm events were used: October 1998, June-July 2002, November 2004, and July 2007. The four events varied greatly in initial soil moisture and, within the catchment, the soil moisture varied greatly with each event. For example, the October 1998 and July 2007 events were considered to have wetter than usual soil moisture conditions. However, in some areas within the catchment, the soil was dryer than the June-July 2002 event which was considered to be a dry event. The November 2004 event was considered to be average soil moisture but the model soil moisture conditions varied across the catchment just as for the other events. Therefore, to determine a dry, wet, and average starting soil moisture conditions, the driest soil loss parameters for each sub-catchment were taken and assigned to a “dry” model, the wettest soil loss parameters were assigned to a “wet” model, and the average soil loss parameters were assigned to an “average” model.

The HEC-HMS model developed by the USACE for flood forecasting was adopted for this study. As with the other two study basins, five series of simulations were run; each series included the 10, 25, 50 and 100 year design storms. The first three series used the USACE developed design storms over wet, dry, and average basin conditions. The final two series were the MPE-based design storms using the median and maximum envelope ARF curves with average basin conditions. These 5 sets of hydrologic simulations demonstrate the effect that the variability in initial soil moisture conditions has on lake inflows compared to varied rainfall volumes.

The storm location and orientation were developed to maximize inflow into Canyon Lake. The same storm center and orientation was used in this study. The 100-year design storm is shown in Figure 5-3 as an example.

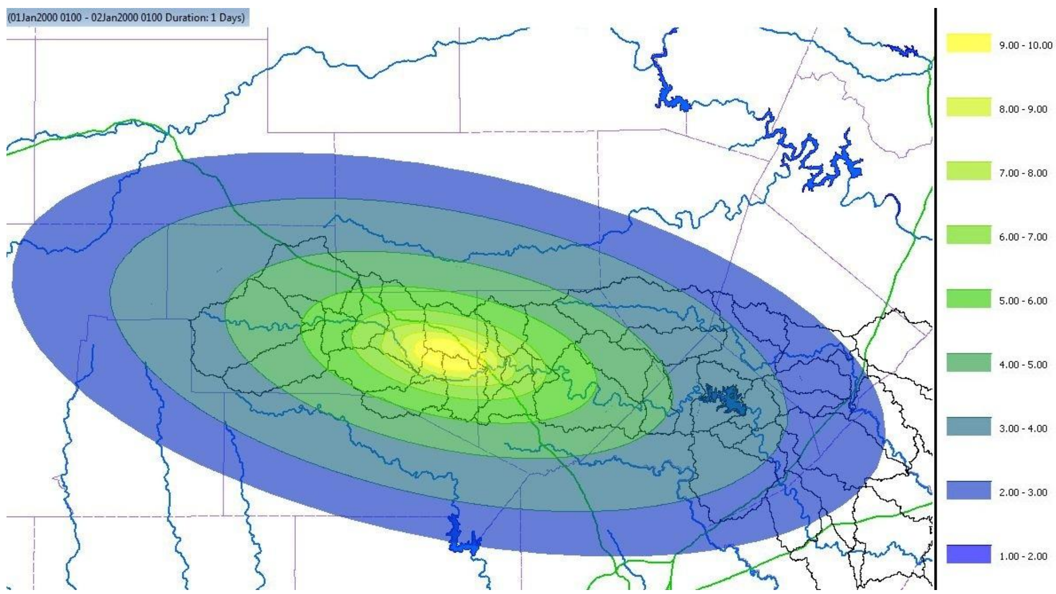


Figure 5-3 Guadalupe River design storm location and orientation

Chapter 6

Results

The design storms that were detailed in the previous sections were simulated in the USACE hydrologic modeling tool, HEC-HMS. These hydrologic simulations were run as semi-distributed models. Based on the depth-area-duration curves and areal-reduction factor curves, one may expect the runoff to be lower than using the previous areal-reduction factors from the baseline storms.

Upper Trinity River Results

Five series of four hydrologic simulations were run and the peak flow at the Dallas gauge on the main stem of the Trinity River was recorded. For each return period simulated, the point rainfall remained the same; the only element that changed was the areal-reduction factor curve and the initial soil moisture conditions. For example, the 100-year point rainfall depth was 9.6 inches of rainfall for all 5 sets of simulations. The change in areal-reduction factors from the USACE ARF curve to the median MPE ARF curve caused a decrease in rainfall volume of 35%. The hydrologic modeling results can be found in the table below.

Table 6-1 Upper Trinity River hydrologic modeling results

Trinity River at Dallas USGS Gage 08057000 (CFS)				
Return Period	10YR	25YR	50YR	100YR
Baseline Study -Wet Conditions - USACE ARF Curve	57,200	80,900	101,400	118,800
Baseline Study - Average Conditions - USACE ARF Curve	47,200	67,600	88,900	107,900
Baseline Study - Dry Conditions - USACE ARF Curve	41,200	56,300	75,000	94,600
UTA Study - Average Conditions - Maximum ARF Curve	39,900	57,200	75,400	94,000
UTA Study - Average Conditions - Median ARF Curve	29,900	42,100	55,700	70,400

The peak discharge rates from this median design storm were much lower than the baseline study. Even with average soil moisture conditions, the decrease in rainfall volume was so significant that the peak discharges were lower than the “Dry” baseline simulation. With the maximum envelope ARF design storm, the peak discharge was close to the “Dry” baseline simulation.

Sulphur River Results

Five series of four hydrologic simulations were run and the pool elevations and inflow volumes at Wright Patman Dam were recorded. As with the Upper Trinity River model simulations, the point rainfall stayed consistent for each set of return period simulations. The change in areal-reduction factors from the USACE ARF curve to the median MPE ARF curve caused a decrease in rainfall volume of 26%. The hydrologic modeling results can be found in the table below.

Table 6-2 Sulphur River hydrologic modeling results

Sulphur River Hydrologic Modeling Results	**Wright Patman 24 Hour Peak Inflow (cfs)**			
Return Period	**10YR**	**25YR**	**50YR**	**100YR**
Baseline Study - Wet Conditions - USACE ARF Curve	92,100	117,400	137,800	161,900
Baseline Study - Average Conditions - USACE ARF Curve	74,400	100,900	119,800	139,100
Baseline Study - Dry Conditions - USACE ARF Curve	60,100	82,900	103,100	122,100
UTA Study - Average Conditions - Maximum ARF Curve	75,100	101,900	121,000	140,500
UTA Study - Average Conditions - Median ARF Curve	46,700	63,600	77,800	92,900

The inflow volumes from the median design storm simulation were much lower than the baseline study. Even with average soil moisture conditions, the decrease in rainfall volume was so significant that the inflow volumes were lower than the “Dry” baseline simulation. As seen in Figure 4-11, the maximum envelope ARF curve derived from MPE data, closely matches the USACE ARF curve, thus, the similarity in hydrologic modeling results.

Guadalupe River Results

Five series of four hydrologic simulations were run and the pool elevations and inflow volumes at Canyon Dam were recorded. As with the other study basins, the point rainfall depth stayed the same for a given return period, only the initial soil moisture conditions and ARF curves were varied. The change in areal-reduction factors between the USACE ARF curve and the median MPE ARF curve caused a decrease in rainfall volume of 42%. The hydrologic modeling results can be found in the table below.

Table 6-3 Guadalupe River hydrologic modeling results

Guadalupe River Hydrologic Modeling Results	Canyon Peak 24-Hour Average Inflow (cfs)			
Return Period	10YR	25YR	50YR	100YR
Wet Conditions - USACE ARF Curve	90,500	120,700	144,400	170,300
Average Conditions - USACE ARF Curve	28,400	46,900	61,700	77,800
Dry Conditions - USACE ARF Curve	7,700	25,000	42,700	64,100
UTA Study - Average Conditions - Maximum ARF Curve	21,300	36,600	49,700	64,400
UTA Study -Average Conditions - Median ARF Curve	7,700	14,800	21,300	29,800

The inflow volumes from median MPE design storm were much lower than the baseline study. Even with average soil moisture conditions, the decrease in rainfall volume was so significant that the inflow volumes were lower than the “Dry” baseline simulation.

It is important to note that the differences in runoff volume is due not only to the differences in the ARF curves used but also the difference in the period of record used as well as the effects of storm transposition used to increase the sample size in the MPE data-based analysis.

Chapter 7

Trend Analysis

As part of the on-going research at the National Climatic Data Center (NCDC) led by Dr. Dongsoo Kim, extreme precipitation data were analyzed using generalized extreme value distribution. The data covered a period of 1949-2008 and has 765 observation sites in the state of Texas. Data integrity was of utmost importance and measures were taken to ensure the quality. If a rain gauge station missed more than one year's worth of observations, the station was eliminated from the analysis. This reduced the amount of observation stations to a final number of 332.

To identify extreme precipitation, a threshold value was set at the top 1% of daily observations. Any observation above the threshold value was considered extreme precipitation. The threshold value was different for each observation station since the top 1% of observations was different for each station. When a station was missing observations during extreme precipitation events, the nearest station's observation was adopted.

Linear trend generalized extreme value (LTGEV) and no-trend generalized extreme value (NTGEV) distribution models (Kim and Kunkel, 2014) were compared to assess the trend in extreme precipitation in Texas. It was found that there is an upward trend in extreme precipitation in Texas. Technical Paper 40 (Hershfield 1961) also uses a no-trend distribution i.e. a stationary statistical model. In the table below, there is a comparison showing the two no-trend distribution models and linear trend distribution model for the Upper Trinity River.

Table 7-1 Upper Trinity River extreme precipitation trend

Study - Type of Statistical Model	Period of Record	50-YR 24-HR Rainfall
TP-40 - Stationary Distribution	1938-1957	8.6"
No-Trend GEV - Stationary Distribution	1949-2008	7.1"
Linear Trend GEV - Non-stationary Distribution	1949-2008	7.6"

As seen in Table 7-1, the initial estimation of the 50-year, 24 hour rainfall may have been over estimated due to the lack of data. However, the LTGEV model shows a modest increase (<7%) in extreme precipitation. In Table 7-2 is an estimation of peak discharge at the same Dallas stream flow gauge based on the change in frequency rainfall.

Table 7-2 Upper Trinity River estimated peak flows for precipitation trends

Estimated Peak Discharge at Dallas Gage	**50YR**	
Rainfall Depth	**8.6"**	**7.6"**
Baseline Study -Wet Conditions - USACE ARF Curve	101,400	89,200
Baseline Study - Average Conditions - USACE ARF Curve	88,900	78,200
Baseline Study - Dry Conditions - USACE ARF Curve	75,000	66,000
UTA Study - Average Conditions - Updated ARF Curve	55,700	49,000

This analysis using advanced statistical modeling is only preliminary but does highlight the need for updating published extreme precipitation studies. Technical Paper 40 is very outdated, and a longer period of record as well as scientific advances could make a significant difference in published extreme precipitation frequency analysis.

Chapter 8

Flood Frequency Analysis and Implications

Flood frequency analysis is used to set design flood peak discharge or peak flood elevations. This tool is often used to communicate between civil engineers and planners. Flood frequency analysis requires the annual maximum flow data, distribution modeling, and other summary statistical information such as mean, standard deviation, and skewness. This study adopted the U.S. Army Corps of Engineers' standard distribution, the Log-Pearson Type III distribution.

Hydrologic impacts of the work carried out in this thesis may be assessed via flood frequency analysis. The same five series of hydrologic simulations as in Chapter 6 are shown in the next three sections as part of flood frequency analyses.

Upper Trinity River Flood Frequency Analysis and Implications

The Upper Trinity River above the Dallas gauge operated by the USGS has approximately 1,100 square miles of uncontrolled drainage area. The annual peak discharges and the design storm peak discharges were plotted using the Log-Pearson Type III distribution. In the frequency plots in this chapter, the annual peak series will be denoted in red triangles, the baseline studies will be denoted with black lines (wet and dry conditions) and blue lines (average conditions), and the MPE-based design storms will be denoted with a purple line (median ARF curve) and orange line (maximum ARF curve). Finally, the light blue lines represent the 5% and 95% confidence limits of the computed frequency curve.

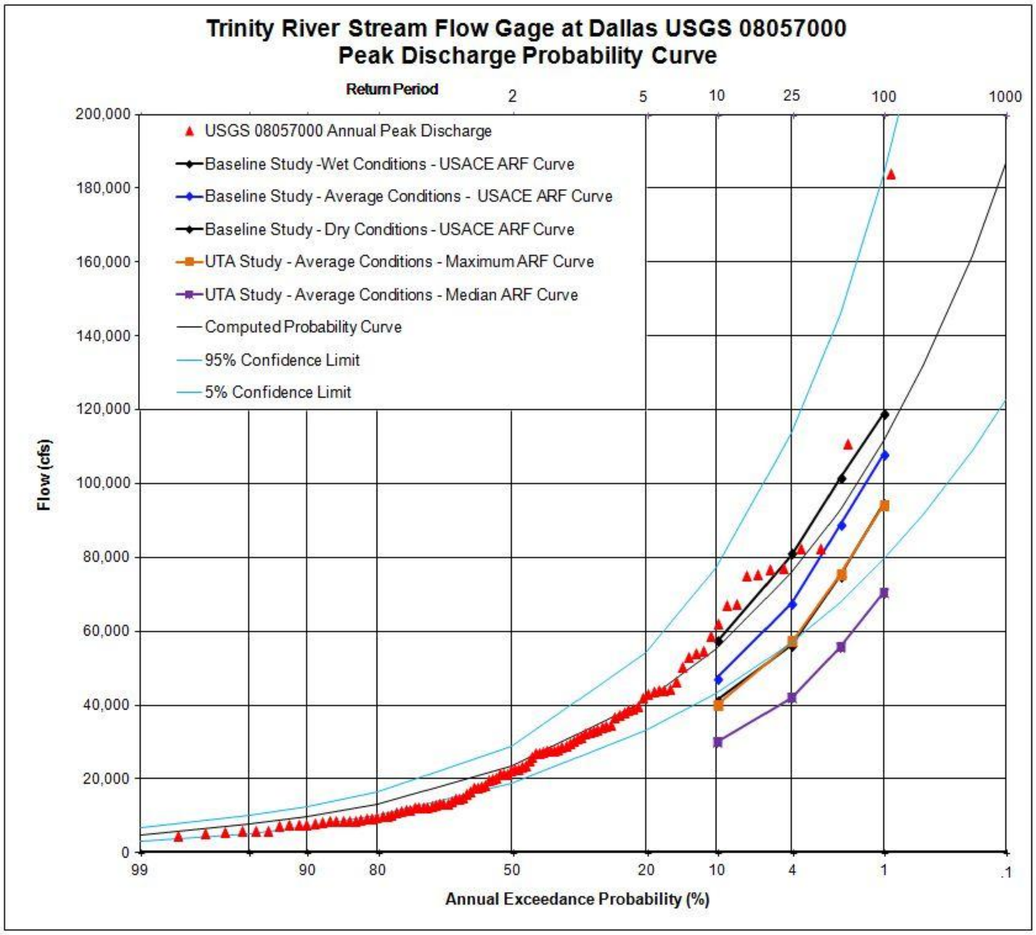


Figure 8-1 Upper Trinity River flood frequency analysis with full period of record

This full period of record (1904-2013) plot indicates the design storms from the USACE baseline study match the fitted probability curve fairly well. However, the updated design storms with the median ARF curves do not have the volume to match the computed flood frequency curve.

Once again, the USACE design storms were based on extreme storms from a period of record of 1894-2008 which closely matches the period of record of peak discharge at the Dallas flow gauge. Flood frequency analysis was also done for the period of record matching the MPE data, 1996-2013, as shown below.

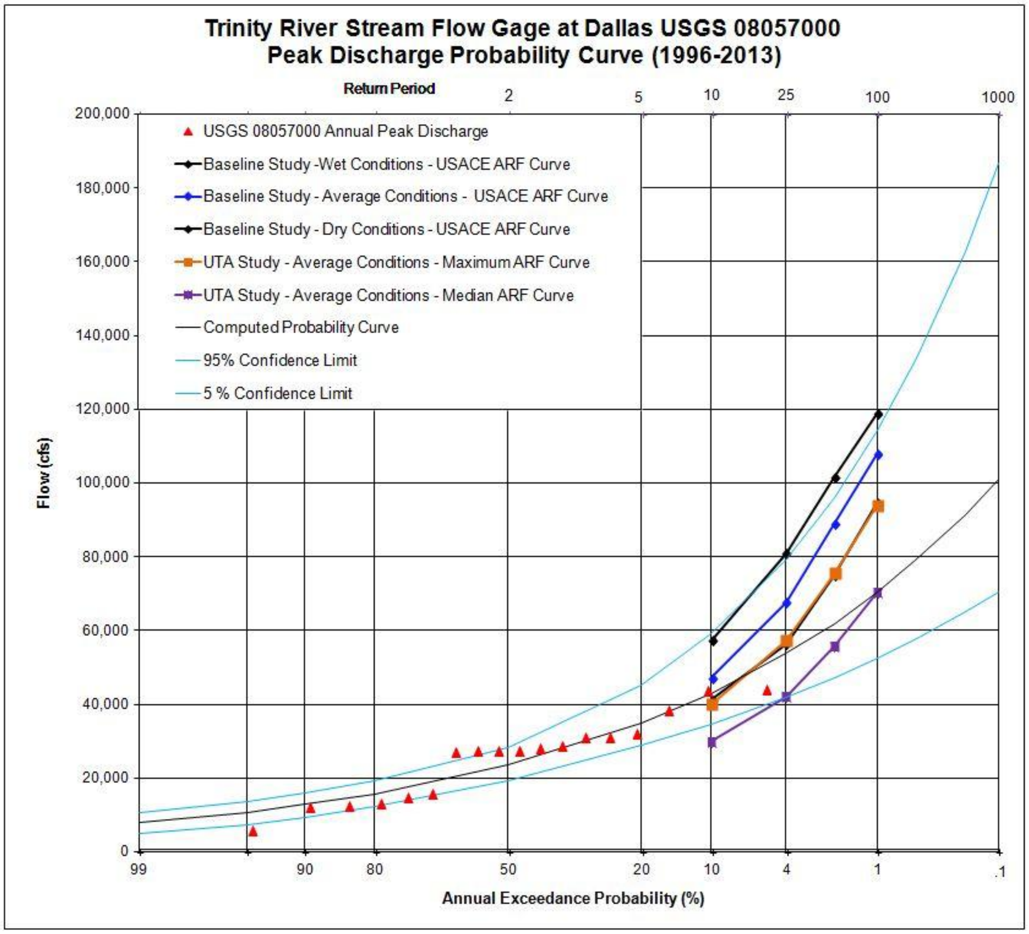


Figure 8-2 Upper Trinity River flood frequency analysis with short period of record

The shortened period of record shows a significant change in flood frequency. There are many factors for changes in flood frequency such as length of record, urbanization, rainfall variation, and soil moisture variation. The above results suggest a downward trend in precipitation volume in extreme storms for the Upper Trinity River region.

Sulphur River Flood Frequency Analysis and Implications

The Sulphur River above Wright Patman Dam has an uncontrolled drainage area of almost 3,000 square miles. Cooper Dam impounds just fewer than 500 of the 3,400 square miles above Wright Patman Dam. The annual maximum 24-hour-average-inflows were distributed using the Log-Pearson Type III distribution and flood frequency curve was computed.

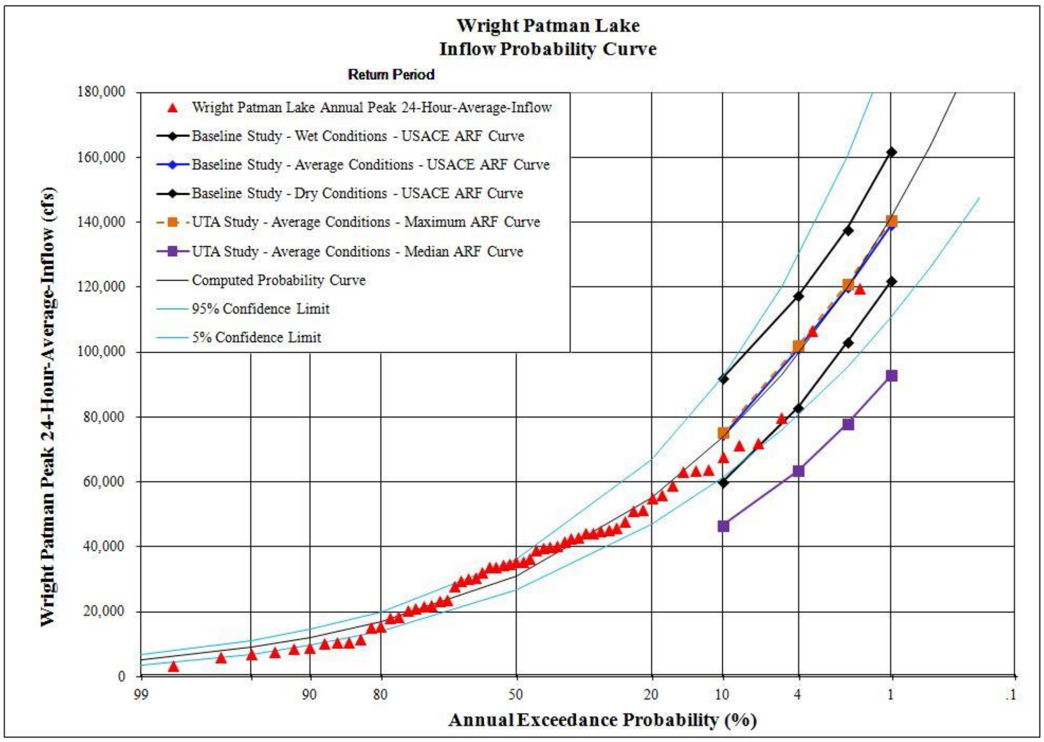


Figure 8-3 Sulphur River flood frequency analysis with full period of record

In this case, the full period of record is 1956-2013 which starts at the time when water began to be impounded at Wright Patman dam. The computed flood frequency curve matches the USACE baseline design storms with average soil moisture conditions, as well as the maximum envelope MPE-based design storm with average soil moisture conditions. This is due to the closeness in the ARF curves in the USACE baseline design storm and the maximum envelope MPE based design storm. The only set of simulations that is clearly outside the confidence limits is the median ARF design storms. Figure 8-4 shows the flood frequency analysis with the same period of record as the MPE data.

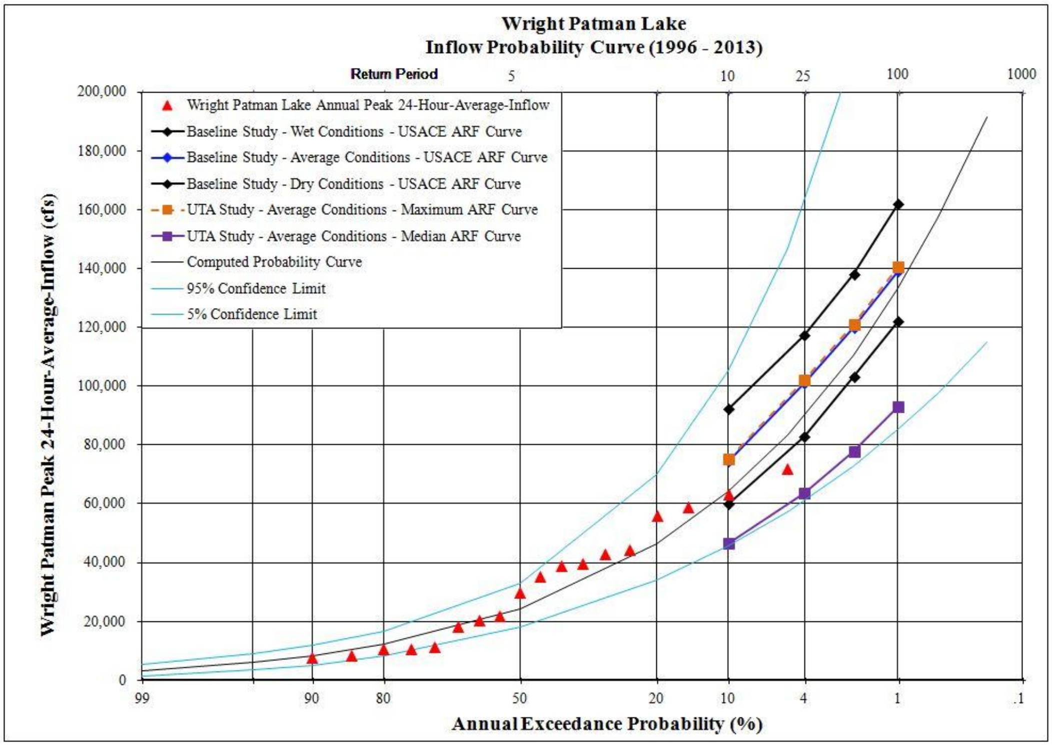


Figure 8-4 Sulphur River flood frequency analysis with short period of record

With the shorter period of record, the computed flood frequency curve falls between the median ARF design storm and the maximum envelope design storm. This again suggests a downward trend in precipitation volume in recent extreme storms in the Sulphur River region.

Guadalupe River Flood Frequency Analysis and Implications

Canyon Dam impounds approximately 1,400 square miles on the Guadalupe River. As with the Wright Patman Dam flood frequency analysis, the annual maximum

24-hour-average-inflows were fitted with Log-Pearson Type III distribution. See Figure 8-5 for the flood frequency analysis of the full period of record, 1964-2013.

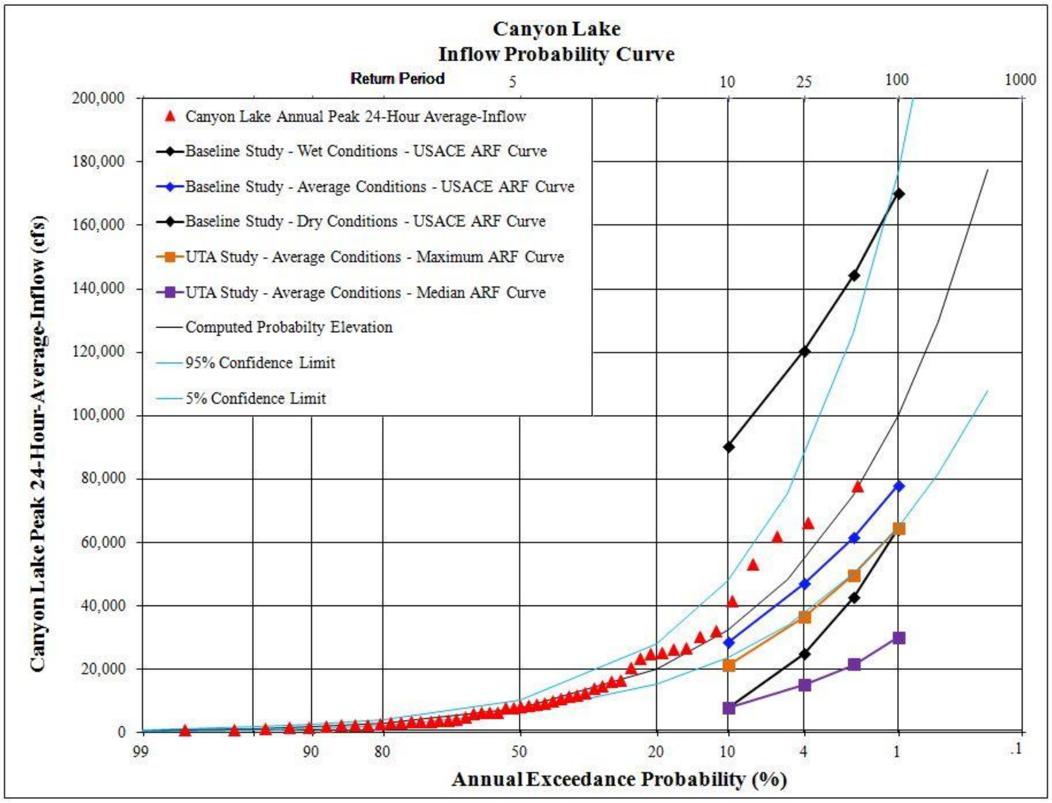


Figure 8-5 Guadalupe River flood frequency analysis with full period of record

This computed flood frequency curve fell closest to the baseline USACE design storm with average soil moisture conditions. The Guadalupe River is much more sensitive to the change in soil moisture than the Sulphur River and Upper Trinity River. The “wet” baseline run is above the computed flood frequency curve while the other 4 series of simulations, including the updated design storms, are below the computed flood frequency curve. This is partially due to the storm events that were used to calibrate the hydrologic model. The June-July 2002 storm event lasted over a week and had more than 6 inches of rain each day over different parts of the watershed. By the end of the event, the soil was saturated and nearly 100% of the rain was runoff even though the storm event began when the soil moisture was dryer than usual.

When the Guadalupe River watershed is at its driest it can soak up water like a sponge. The Guadalupe River is above Edwards' aquifer and much of the rainfall can be lost to infiltration during dry seasons. Since the average initial soil moisture conditions were set as an average from several calibration events, the variability in soil moisture causes an under-estimation of runoff volume. Hence, the wet and dry models for the Guadalupe River represent the bounds for the wettest and driest possible initial soil moisture conditions and the average represent a small under-estimation of runoff volumes.

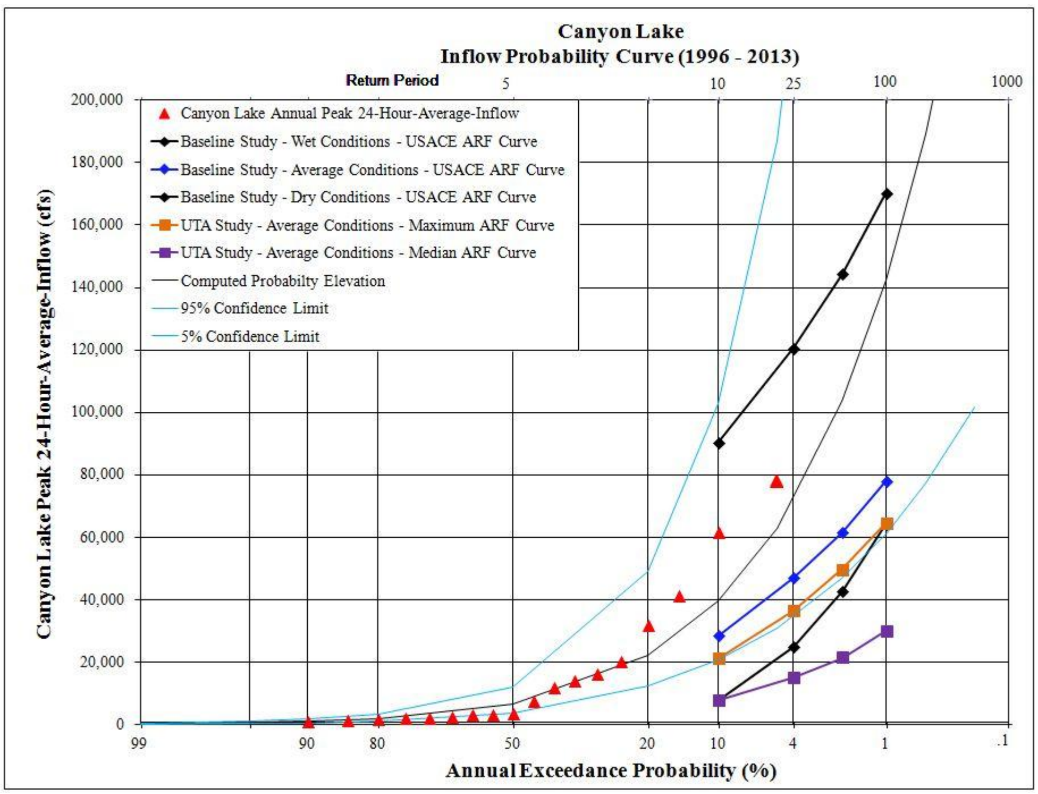


Figure 8-6 Guadalupe River flood frequency analysis with short period of record

In the shorter period of record flood frequency analysis, the flood frequency curve trends upward unlike the Upper Trinity River and the Sulphur River. This could be due to three of the highest five average daily inflows occurring since 1996. In other words, a majority of the extreme storms used in the development of the Guadalupe River design storms actually occurred over the Guadalupe River basin. Therefore, the storms were reflected in both the MPE data and the streamflow gauge records. In contrast, very few of the extreme storms used for the Upper Trinity River and Sulphur River actually occurred over their respective watersheds. They were included in the extreme storm list and therefore affected the development of the ARF curve but weren't reflected in the Upper Trinity River and Sulphur River streamflows. It is expected that if the maximum envelope MPE design storms were simulated with wet initial soil moisture conditions it would closely match the observed period of record data from 1996-2013.

Chapter 9

Summary, Conclusions and Future Recommendations

This study has demonstrated that radar-based precipitation data are a valuable source of information for precipitation and flood frequency analyses. The MPE-based areal-reduction factors were found to be significantly lower than those based on rain gauge observations reported for the same study basins in Texas: the Upper Trinity River, the Sulphur River and the Guadalupe River. There are three plausible explanations: first, the use of radar-based precipitation data provides a more representative depiction of rainfall variability compared to interpolating rain gauge observations; second, sampling uncertainties may be a significant contributing factor in that the period of record used in this study (1996-2013) was much different from that used by the NWS in the Technical Papers (see Chapter 2), and that storm transposition was used in this study to trade space for time. Third, nonstationarity due to climate change may have played a role in the type of storms that have occurred more recently.

This study does provide some indications of combined effects of urbanization and climate change to flood frequency, most notably for the Upper Trinity River. For the Upper Trinity Basin, precipitation amounts from the nonstationary generalized extreme value distribution with linear trend (LTGEV) model are uniformly larger (but by less than 10%) than those of the stationary generalized extreme value distribution with no trend (NTGEV) model for the same return periods, except at the 24-hour duration. There have been very few extreme storms to actually fall over the Upper Trinity River watershed over the last 17 years. The few extreme storms that did occur over the watershed, for which MPE data is available, had smaller precipitation volumes than those recorded by rain gauge networks prior to 1996. However, given the relatively short period of record available for the MPE data, it is not clear at this time whether the above represents a permanent shift in climatology. As such, the results of this study should not be construed as justification for downward-adjusting the design criteria.

This study points to several observations and additional needs. First, Technical Papers 40 and 49 are clearly out of date and NOAA Atlas 14 needs to be produced for Texas. The rainfall frequency atlas should be updated to include over 50 years of additional rainfall data. Second, depth-area-duration (DAD) relationships need to be refined; different DAD relationships may be considered for different return periods, or ranges of return periods, as well as for more diverse climatic regions. This study indicates that additional research is needed for a state-wide or nationwide study on DAD relationships for extreme precipitation to capture stochasticity not only in point precipitation but also in the areal reduction factor (ARF). Third, the science and application of synthetic design storms needs to be refined. As tools such as HEC-MetVue evolve, design storms are easier to develop and apply in hydrologic design studies. For synthetic design storms to be an appropriate input in flood frequency analysis, the design storm flood should reflect the historical data of that region..

One may argue that, to reflect large spatiotemporal variability in extreme precipitation, stochastic storm transposition (SST) should replace the design storm when performing flood frequency analysis. While desirable in theory, SST is much more difficult to implement in current hydrologic engineering practices. This study, on the other hand, used free software tools that are made available by the federal government and therefore may be carried out by anyone.

Appendix A

Storm Database

. Table A-1 Storm database

Start Date	Duration	Type of Rain	Location	State	Total 10 Sq. Mi. depth (In)	Max 24 hr 10 Sq. Mi. depth (In)	Areal extent (Sq. Mi.)	Latitude	Longitude
12/20/1997	48	Convective	Waco	TX	7.96	7.93	110,000	31.6478	-97.2439
1/4/1998	96	Convective	Apple Springs	TX	10.85	8.85	180,000	31.2400	-95.0886
8/22/1998	96	Tropical Storm	Del Rio	TX	15.27	9.23	93,000	29.3869	-100.7161
10/17/1998	48	Tropical Depression	Garwood	TX	28.21	26.22	130,000	29.4058	-96.3475
12/15/2001	72	Convective	Terrell	TX	10.51	9.07	120,000	32.7117	-96.3528
6/30/2002	168	Tropical Storm	Center Point	TX	41.36	10.91	300,000	29.9139	-99.0764
10/17/2002	48	Convective	Dallas	TX	10.63	10.15	130,000	32.7936	-96.7211
11/15/2003	72	Convective	Kountze	TX	14.52	8.51	410,000	30.3458	-94.4517
5/11/2004	96	Convective	Pitkin	LA	14.59	12.62	210,000	31.0175	-92.8144
6/5/2004	144	Convective	Medina	TX	13.89	7.83	270,000	29.8392	-99.4036
6/25/2004	192	Convective	D'Hanis	TX	12.91	9.99	470,000	29.3411	-99.2231
7/24/2004	96	Convective	Mansfield	TX	14.99	12.94	190,000	32.5533	-97.1011
8/8/2005	72	Frontal	Moody	TX	10.98	6.11	95,000	31.2072	-97.4000
8/13/2005	96	Frontal	Davis	OK	10.72	5.25	280,000	34.4319	-97.1778
9/23/2005	96	Tropical Storm	Jasper	TX	17.92	17.84	350,000	30.8989	-94.1664
3/18/2006	72	Convective	Grand Prairie	TX	9.90	8.75	250,000	32.6886	-97.0361
10/15/2006	120	Tropical Depression	Kountze	TX	20.14	15.50	570,000	30.3947	-94.3186
1/13/2007	72	Convective	Jefferson	TX	8.98	6.85	120,000	32.8031	-94.2431
5/24/2007	96	Convective	Fredericksburg	TX	10.43	9.74	260,000	30.3114	-98.8672
6/25/2007	96	Convective	Marble Falls	TX	18.07	16.25	240,000	30.5922	-98.1842
8/16/2007	96	Tropical Depression	San Antonio	TX	12.91	11.38	220,000	30.0978	-98.8136
3/17/2008	72	Convective	Chadwick	MO	15.74	13.26	150,000	36.9533	-92.8600
8/16/2008	120	Convective	Ryan	OK	11.69	10.21	430,000	34.1150	-97.9289
9/1/2008	96	Tropical Depression	Larto Lake	LA	22.57	14.25	310,000	31.1500	-92.1975
9/9/2008	96	Convective	Estelline	TX	10.72	8.99	200,000	34.4447	-100.5944
9/13/2008	48	Hurricane	Spring	TX	20.03	16.55	180,000	30.1617	-95.5442
4/16/2009	96	Convective	Schulenburg	TX	14.13	10.40	220,000	29.7081	-96.8308
4/27/2009	96	Convective	St. Jo	TX	13.43	11.77	220,000	33.8969	-97.5703
5/1/2009	72	Convective	Tyler	AR	8.51	6.78	290,000	34.7156	-91.6439
5/9/2009	72	Convective	Clarksville	TX	13.58	5.37	89,000	33.6306	-94.9250
9/10/2009	144	Convective	Hampton	AR	18.74	13.41	430,000	33.5272	-92.5500
10/21/2009	48	Convective	Kingsland	TX	8.63	8.57	260,000	30.6206	-98.4642
10/29/2009	72	Convective	Livingston	TX	8.75	7.92	340,000	30.9281	-95.0247
4/15/2010	72	Convective	Quitaque	TX	12.49	9.15	170,000	34.4017	-101.0786
6/9/2010	72	Convective	Coolidge	TX	13.87	7.04	93,000	31.8272	-96.6772
6/13/2010	72	Convective	Perryton	TX	10.61	9.18	110,000	36.1667	-100.8369
7/1/2010	144	Tropical Storm	Coahuila	MEX	43.79	8.84	420,000	28.5308	-101.8714
9/7/2010	72	Tropical Storm	Georgetown	TX	14.33	11.68	230,000	30.7175	-97.7197
1/25/2012	24	Convective	Martindale	TX	8.75	8.75	200,000	29.7931	-97.8553
9/27/2012	96	Convective	Nacogdoches	TX	13.02	8.56	380,000	31.5900	-94.7208
7/15/2013	72	Convective	Cisco	TX	12.50	5.86	300,000	32.2272	-99.1239
10/12/2013	120	Convective	Carrizo Springs	TX	15.29	4.17	320,000	28.5389	-99.8578
10/30/2013	48	Convective	Teague	TX	16.80	15.45	310,000	31.5675	-96.3067

Appendix B

Design Storm Information

Table B-1 Design storm unit hyetographs

24-Hour Storm Unit Hyetograph		96-Hour Storm Unit Hyetograph							
Tme Step (Hour)	Rainfall Depth (Inches)	Tme Step (Hour)	Rainfall Depth (Inches)	Tme Step (Hour)	Rainfall Depth	Tme Step (Hour)	Rainfall Depth	Tme Step (Hour)	Rainfall Depth
1	0.0085	1	0.001082	25	0.00189	49	0.01055	73	0.00135
2	0.0091	2	0.001082	26	0.00189	50	0.01055	74	0.00135
3	0.0099	3	0.001082	27	0.00189	51	0.01055	75	0.00135
4	0.0108	4	0.001082	28	0.00189	52	0.01055	76	0.00135
5	0.0119	5	0.001082	29	0.00189	53	0.01055	77	0.00135
6	0.0133	6	0.001082	30	0.00189	54	0.01055	78	0.00135
7	0.0196	7	0.002163	31	0.00379	55	0.02245	79	0.00298
8	0.0226	8	0.002163	32	0.00379	56	0.02245	80	0.00298
9	0.0269	9	0.002163	33	0.00379	57	0.02245	81	0.00298
10	0.0364	10	0.002163	34	0.00379	58	0.02245	82	0.00298
11	0.0504	11	0.002163	35	0.00379	59	0.02245	83	0.00298
12	0.0932	12	0.002163	36	0.00379	60	0.02245	84	0.00298
13	0.4492	13	0.001893	37	0.00379	61	0.02217	85	0.0027
14	0.0545	14	0.003245	38	0.00595	62	0.03488	86	0.00433
15	0.0420	15	0.007572	39	0.0146	63	0.08383	87	0.01082
16	0.0299	16	0.01974	40	0.03732	64	0.2166	88	0.02758
17	0.0245	17	0.004327	41	0.00838	65	0.04895	89	0.00622
18	0.0210	18	0.002434	42	0.0046	66	0.02704	90	0.00352
19	0.0141	19	0.001352	43	0.00243	67	0.01433	91	0.00189
20	0.0125	20	0.001352	44	0.00243	68	0.01433	92	0.00189
21	0.0113	21	0.001352	45	0.00243	69	0.01433	93	0.00189
22	0.0103	22	0.001352	46	0.00243	70	0.01433	94	0.00189
23	0.0095	23	0.001352	47	0.00243	71	0.01433	95	0.00189
24	0.0088	24	0.001352	48	0.00243	72	0.01433	96	0.00189

.

Table B-2 Design storm critical storm locations

Critical Storm Locations	Latitude	Longitude	Rotation (°)	Elevation (Feet)
Upper Trinity River	32.7797	-97.2842	36°	912
Sulphur River	33.3764	-95.2489	1°	486
Guadalupe River	29.9922	-98.9961	12°	1634

Note: Storm rotations are measured from the East-West axis to the primary storm axis, rotating counter-clockwise.

Appendix C

Areal-Reduction-Factor Comparisons

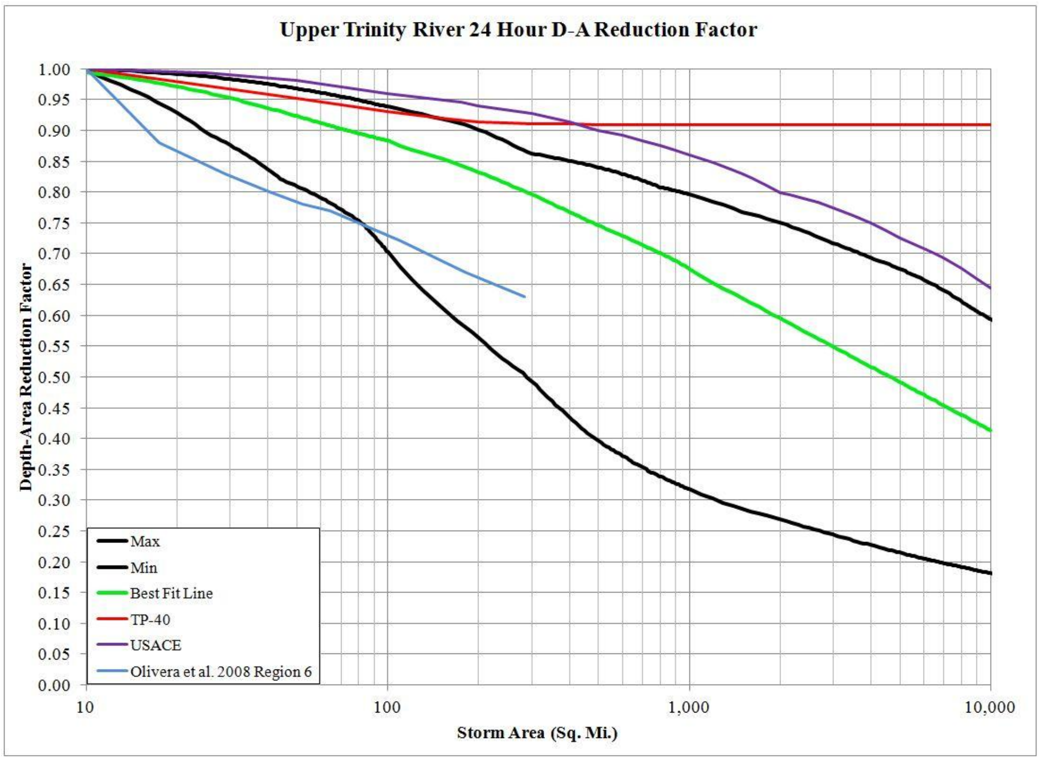


Figure C-1 Upper Trinity River ARF comparison with Olivera et al., 2008

Note: The Sulphur River could not be compared due to the longer storm duration of 96 hours used in this study. Olivera's ARF curves were only for storms of up to 24 hours.

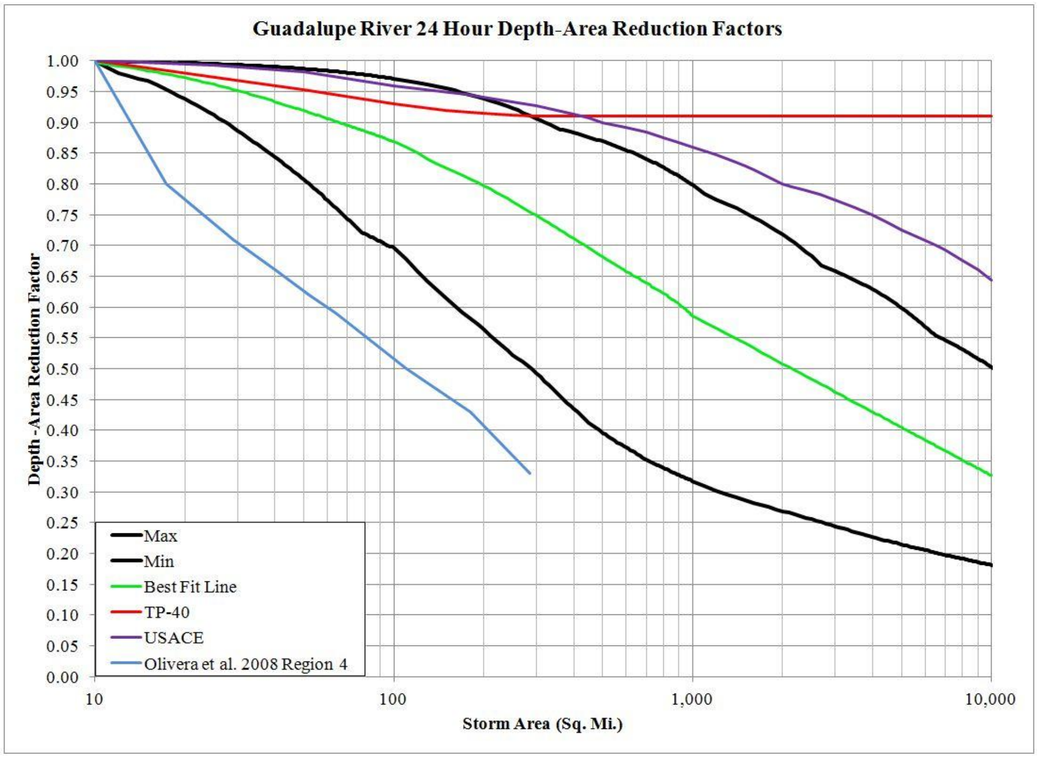


Figure C-2 Guadalupe River ARF comparison to Olivera et al., 2008

Appendix D

Derived Distribution for Precipitation Volume

The storm-specific ARF curves for the three studies areas indicate very large variability. As such, it is necessary to account for this variability when developing flood frequency curves. The purpose of this appendix is to develop a very simple model for precipitation volume that reflects not only the stochasticity of precipitation amount but also that of the ARF. Empirical evidence (see Figures D-1 though D-3) suggests that precipitation amount (x-axis) and ARF are mildly correlated.

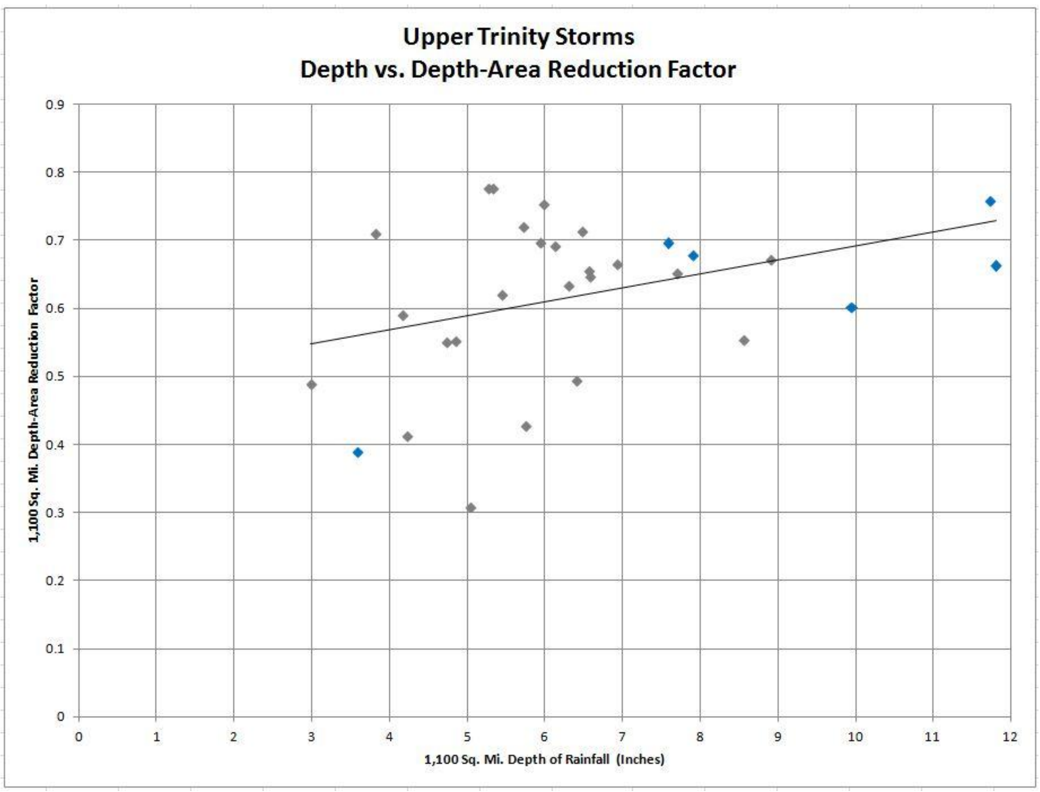


Figure D-1 Rainfall depth versus ARF at the catchment scale for the Upper Trinity River

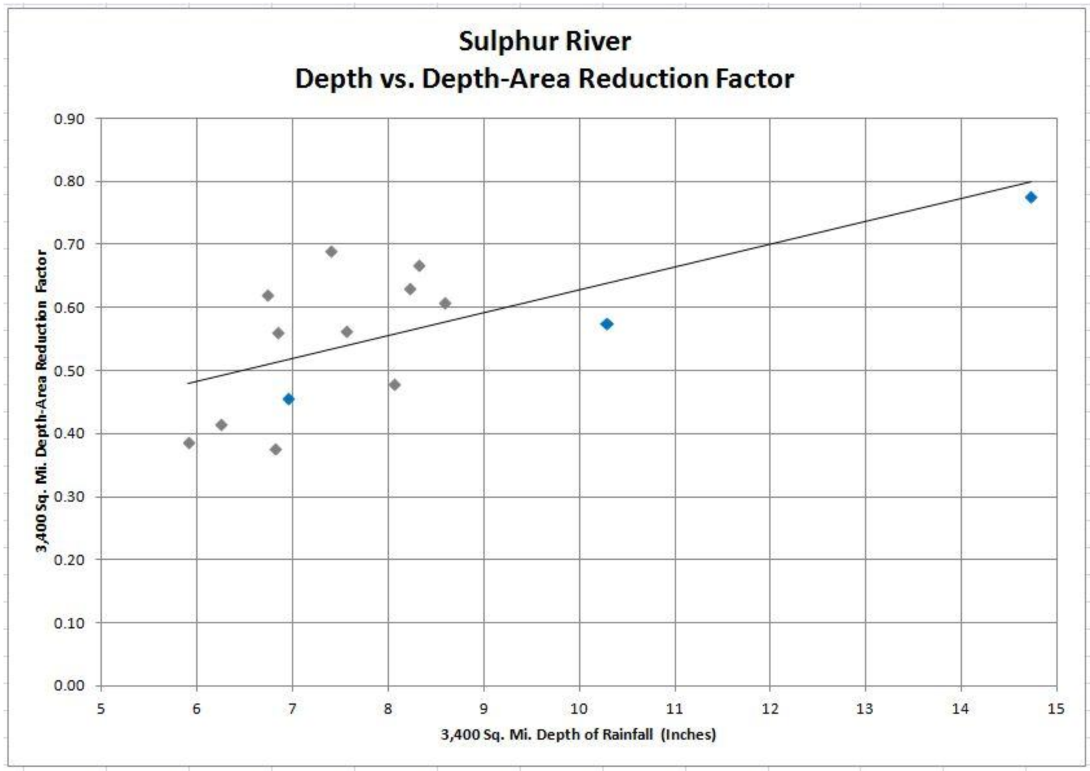


Figure D-2 Rainfall depth versus ARF at the catchment scale for the Sulphur River

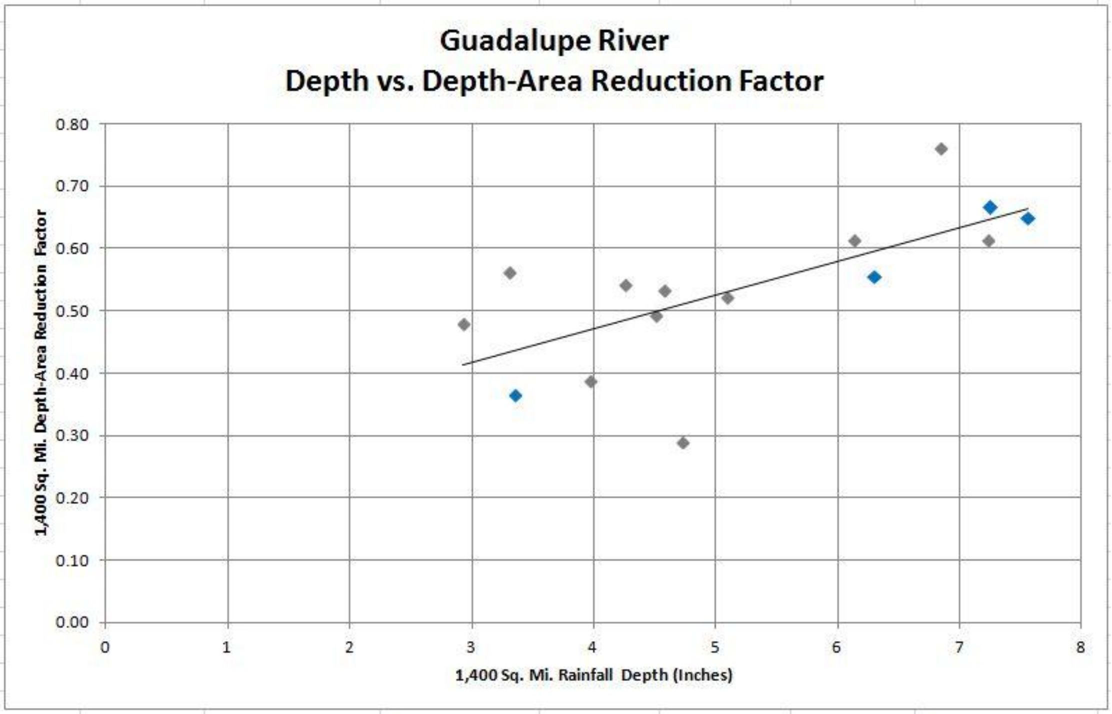


Figure D-3 Rainfall depth versus ARF at the catchment scale for the Guadalupe River

To Model stochasticity of ARF and dependence of the rate of its decrease in magnitude of point precipitation, we assume the following idealized shape for the design storm.

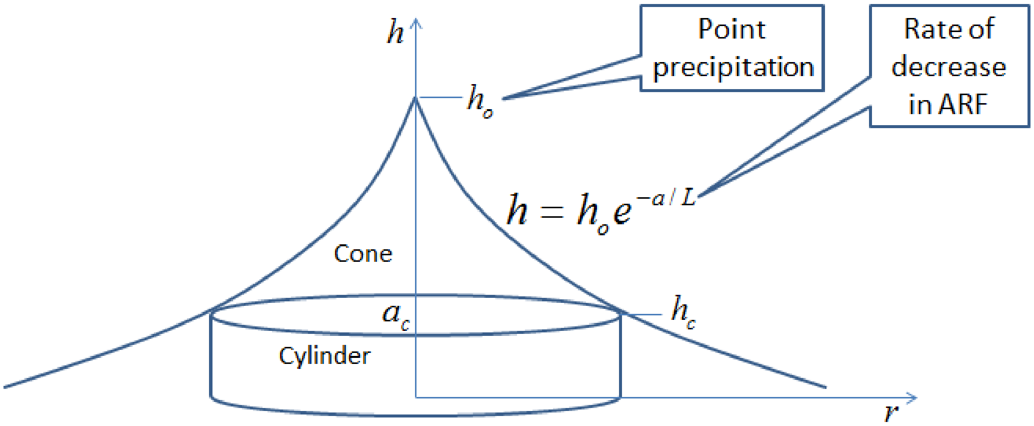


Figure D-4 Idealized design storm

Then, the total precipitation volume over the catchment of area a_c is given by:

$$V = Cylinder + Cone = (h_o - h_c)L$$

Equation D-1

In the above equation, we model h_o as two-parameter Gumbel and limit the range of L to the slowest and the fastest decreasing ARF (upper- and lower-bounds in the ARF spaghetti plot). We then carry out the following two Monte-Carlo experiments in which L is assumed to be uniformly distributed:

Experiment 1 – Assume h_o and L are statistically independent, and

Experiment 2 – Assume h_o and L are statistically dependent (see next slide)

From the empirical relationship shown in Figures D-1 through D-3, we model the dependence between the rate of decrease in ARF and magnitude of point precipitation as:

$$\frac{h_c}{h_o} = \alpha \frac{V}{a_c} + \beta$$

Equation D-2

Then, using the expression for V in the previous slide, we may relate L with h_o as follows:

$$e^{-\frac{a_c}{L}} = \frac{\alpha}{a_c} h_o (1 - e^{-\frac{a_c}{L}}) L + \beta$$

Equation D-3

Once an experimental value of L is obtained by solving the above equations, a uniform random noise is added to obtain the Monte-Carlo simulation results shown in Figure D-5.

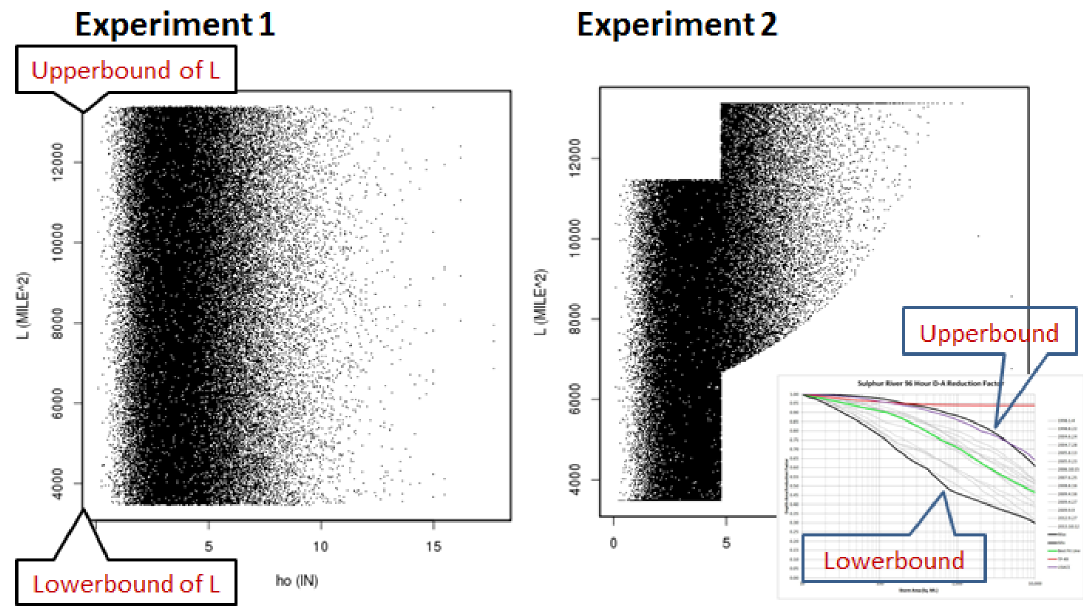
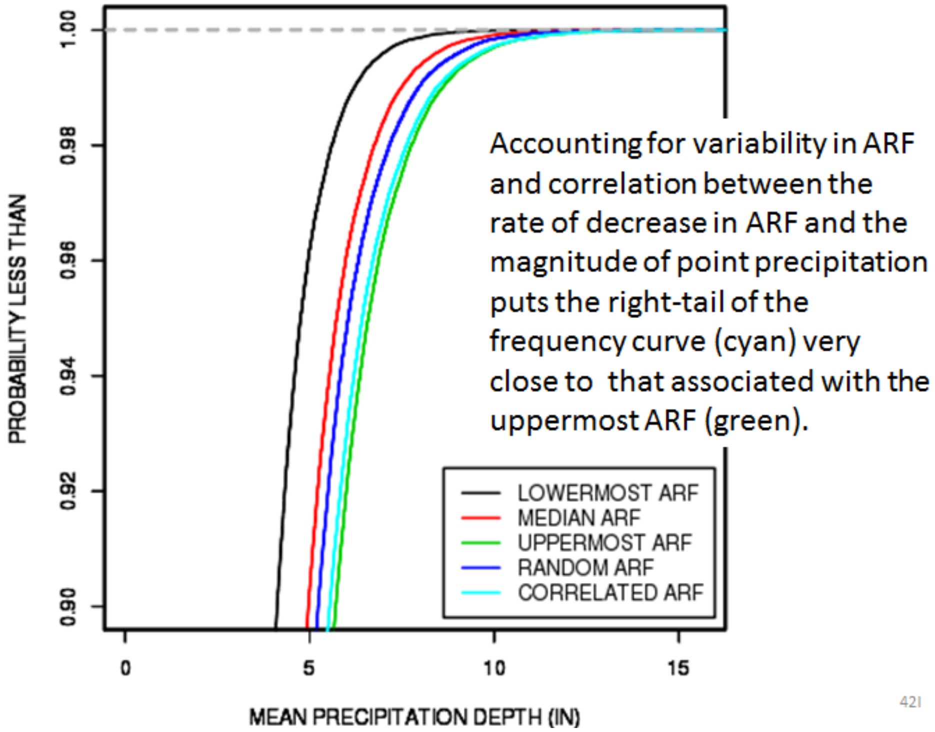


Figure D-5 Modeling independence and dependence between h_o and L for Experiments 1 and 2, respectively

From Equation D-3, we obtain the derived distribution of precipitation volume, V, as shown in Figure D-6. Note that the distribution of V based on correlated ARF follows very closely that associated with maximum ARF. It suggests that, to account for the variability in ARF in addition to that in point precipitation, using the maximum ARF curve is a reasonable (though somewhat biased on the high side) approximation.



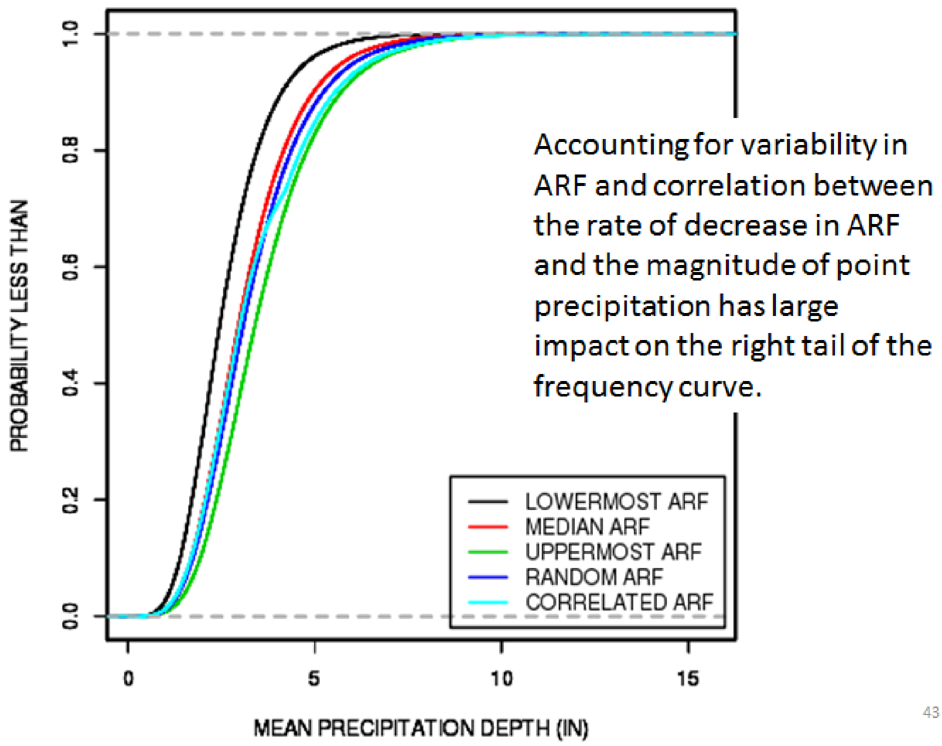


Figure D-6 Derived distribution of V for the upper tail only (top) and for the full range (bottom)

References

Corrigan, P. *Probable Maximum Precipitation for California Calculation Procedures*. Silver Spring, MD: U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, 1999. Print.

Chow, Ven Te, David R. Maidment, and Larry W. Mays. *Applied Hydrology*. New York: McGraw-Hill, 1988. Print.

Demargne, Julie, Limin Wu, Satish Regonda, James Brown, Haksu Lee, Minxue He, Dong-Jun Seo, Robert Hartman, Henry D. Herr, Mark Fresch, John Schaake, and Yuejian Zhu. "The Science of NOAA's Operational Hydrologic Ensemble Forecast Service." *Bulletin of the American Meteorological Society* (2014): 79-98. Web.

England, John F., Pierre Y. Julien, and Mark L. Velleux. "Physically-based Extreme Flood Frequency with Stochastic Storm Transposition and Paleoflood Data on Large Watersheds." *Journal of Hydrology* 510 (2014): 228-45. Web.

Frederick, Ralph H., Vance A. Myers, and Eugene P. Auciello. *Five- to Sixty-Minute Precipitation Frequency for the Eastern and Central United States*. Silver Spring, MD: U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, 1977. Print.

Hansen, E. Marshall., L. C. Schreiner, and John F. Miller. *Application of Probable Maximum Precipitation Estimates: United States East of the 105th Meridian*. Washington, D.C.: U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, 1982. Print.

Hershfield, David M., Walter T. Wilson, and William E. Hiatt. *Rainfall Intensity-frequency Regime. Part 2 - Southeastern United States*. Washington, D.C.: U. S. Department of Commerce, Weather Bureau, 1958. Print.

Hershfield, David M. *Rainfall Frequency Atlas of the United States: For Durations from 30 Minutes to 24 Hours and Return Periods from 1 to 100 Years*. Washington: Dept. of Commerce, Weather Bureau, 1961. Print.

Kappel, Bill, Ed Tomlinson, Courtney Jalbert, and Louie Verreault. *Site-Specific PMP for North Texas: Bringing HMR 51 into the 21st Century*. Proc. of United States Society on Dams 2012 Annual Meeting and Conference, New Orleans, LA. Monument, CO: Applied Weather Associates, 2012. Web.

Kim, Dongsoo, and Kenneth E. Kunkel. *Extreme Precipitation Trend Estimation in Conterminous United States (CONUS)*. Proc. of Donald R. Johnson Symposium, Georgia World Congress Center, Atlanta, GA. Asheville, NC: National Oceanic and Atmospheric Administration and National Climatic Data Center, 2014. Web.

Kunkel, Kenneth E., Thomas R. Karl, Harold Brooks, James Kossin, Jay H. Lawrimore, Derek Arndt, Lance Bosart, David Changnon, Susan L. Cutter, Nolan Doesken, Kerry Emanuel, Pavel Ya. Groisman, Richard W. Katz, Thomas Knutson, James O'brien, Christopher J. Paciorek, Thomas C. Peterson, Kelly Redmond, David Robinson, Jeff Trapp, Russell Vose, Scott Weaver, Michael Wehner, Klaus Wolter, and Donald Wuebbles. "Monitoring and Understanding Trends in Extreme Storms: State of Knowledge." *Bulletin of the American Meteorological Society* 94.4 (2013): 499-514. Web.

Miller, John F. *Two- to Ten-day Precipitation for Return Periods of 2 to 100 Years in the Contiguous United States*. Washington, D.C.: U.S. Dept. of Commerce, Weather Bureau, 1964. Print.

Olivera, Francisco, Janghwoan Choi, Dongkyun Kim, and Ming-Han Li. "Estimation of Average Rainfall Areal Reduction Factors in Texas Using NEXRAD Data." *Journal of Hydrologic Engineering* 13.6 (2008): 438. Print.

Schreiner, L. C., and John T. Riedel. *Probable Maximum Precipitation Estimates, United States East of the 105th Meridian*. Washington: Dept. of Commerce, National Oceanic and Atmospheric Administration, 1978. Print.

Seo, D.-J., H. D. Herr, and J. C. Schaake. "A Statistical Post-processor for Accounting of Hydrologic Uncertainty in Short-range Ensemble Streamflow Prediction." *Hydrology and Earth System Sciences Discussions* 3.4 (2006): 1987-2035. Print.

Seo, D.-J., A. Seed, and G. Delrieu. "Radar-based Rainfall Estimation." *Rainfall: State of the Science*. Ed. Firat Y. Testik and Mekonnen Gebremichael. Washington, DC: American Geophysical Union, 2011. Print.

U.S. Army Corps of Engineers. Fort Worth District Office. *Corridor Development Certificate Hydrologic and Hydraulic Model Update*. Comp. Bret Higginbotham. Fort Worth, TX, 2012. Print.

U.S. Army Corps of Engineers. Fort Worth District Office."Hydrologic Loading." *Periodic Assessment of Dam Safety for Wright Patman Dam*. By Allen Avance. Fort Worth, TX, 2014a. Print.

U.S. Army Corps of Engineers. Fort Worth District Office. *Corps Water Management System Final Report for the Guadalupe River*. By Charles L. Erickson. Comp. Helena P. Mosser. Fort Worth, TX, 2014b. Print.

Wright, Daniel B., James A. Smith, and Mary Lynn Baeck. "Flood Frequency Analysis Using Radar Rainfall Fields and Stochastic Storm Transposition." *Water Resources Research* 50.2 (2014): 1592-1615. Print.

Biographical Information

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