U.S. Army Corps of Engineers
Texas Storm Study: Summary Report

FINAL

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Abbreviations

AORC	Analysis of Record for Calibration
DARF	Depth-Area-Reduction Factor
FEMA	Federal Emergency Management Agency
GCM	Global Climate Model
IBPM	Idealized Basin Precipitation Maximization
IEM	Iowa Environmental Mesonet
InFRM	Interagency Flood Risk Management
MPE	Multisensor Precipitation Estimates (MPE)
MRMS	Multi-Radar/Multi-Sensor
NOAA	National Oceanic and Atmospheric Administration
PRISM	Parameter-elevation Relationships on Independent Slopes Model
RFC	River Forecast Center
SPAS	Storm Precipitation Analysis System
TP	Technical Paper
TSS	Texas Storm Study
TxGLO	Texas General Land Office
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WHA	Watershed Hydrologic Assessment

Definitions

Point Precipitation: Corresponds to the precipitation depth at a point, usually measured by a rain gage. National Oceanic and Atmospheric Administration (NOAA) Atlas 14 provides point precipitation estimates with multiple return periods and durations.

Areal Precipitation: Attributed to the spatial distribution of precipitation, areal precipitation is expected to decrease as area increases. Areal precipitation is the expected precipitation with multiple durations and return periods expected over a watershed of interest.

Depth-Area-Reduction Factor (DARF): A factor used to convert point precipitation into areal precipitation. Due to the spatial distribution of precipitation, areal precipitation is expected to decrease as area increases. The DARF represents that decrease and allows the correction of the point precipitation when it is applied over a larger area. The DARF varies between 0 and 1, with a value of 1 meaning that the entire area observes the same precipitation as the point measurement; this happens if the area of interest is very small.

Statistical-based peak discharge frequency analysis: Relies on statistical methods to estimate peak discharge with multiple return periods. The recommended method in the United States is Bulletin 17C proposed by U.S. Geological Survey (USGS) (England et al, 2018). The application of this method requires a continuous, long, time-series of discharge measurements, which is not always available. An alternative approach that overcomes this issue is the model-based peak discharge frequency analysis.

Model-based peak discharge frequency analysis: Relies on calibrated hydrological models and realistic design storms to estimate peak discharge with multiple return periods. The application of this method requires a continuous, long, time-series of precipitation measurements, which is more accessible and available than discharge measurements. The method also requires realistic design storms—the focus of this study—and a calibrated hydrological model.

Acknowledgements

The Water Resources Branch of the U.S. Army Corps of Engineers Fort Worth District would like to acknowledge the world-class efforts of the project team. This study has very few precedents, as highlighted in the literature review, underscoring the project's difficulty. The team quickly unified, worked diligently to support one another, and successful completed a challenging mission. This exceptional accomplishment is largely due to team's dedication, with each member playing a crucial role in its success.

- Thank you to WEST Consultants for serving as the project lead, maintaining the schedule, and conducting the storm analysis.
- Thank you to the University of Texas at Arlington Team for bringing energy and innovation to the project, along with the tireless efforts.
- Thank you to the Texas A&M Team for contributing technical expertise, wisdom, and stability.
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Special thanks to Dr. William Asquith and Glenn Harwell of the USGS, Dr. Nelun Fernando of the Texas Water Development Board, and Allison Wood of Huitt-Zollars, for their contributions to the peer-review process.

Foreword by Mr. Jerry Cotter, P.E.

As the eight largest economy among the nations of the world (Texas Economic Development & Tourism, 2024) and the second largest economy among the U.S. (Texas Economic Development & Tourism, 2024), Texas plays a critical role in both the U.S. and the world economies. Texas ranks first in exports among U.S., exporting nearly $300 billion annually in natural resources such as oil, coal, and natural gas, as well as agricultural products. (Schattenberg, 2021). According to a recent report from the U.S. Department of Energy, Texas is responsible for over 40% of domestic oil production and around 30% of U.S. refinery production (U.S. Energy Information Administration, 2024). As of 2023, Texas is home to 54, Fortune 500 company headquarters (Texas Office of the Governor, 2023).

Weather significantly impacts a region's people, economy, and agricultural production. As illustrated in Figure A (TWDB, 2012), Texas is uniquely positioned on the Globe to experience seasonal air masses from the Gulf of Mexico, the Arctic North, and the Pacific Jet Stream. This positioning results in extensive natural climate variability, causing dramatic shifts between extreme drought and extreme floods.

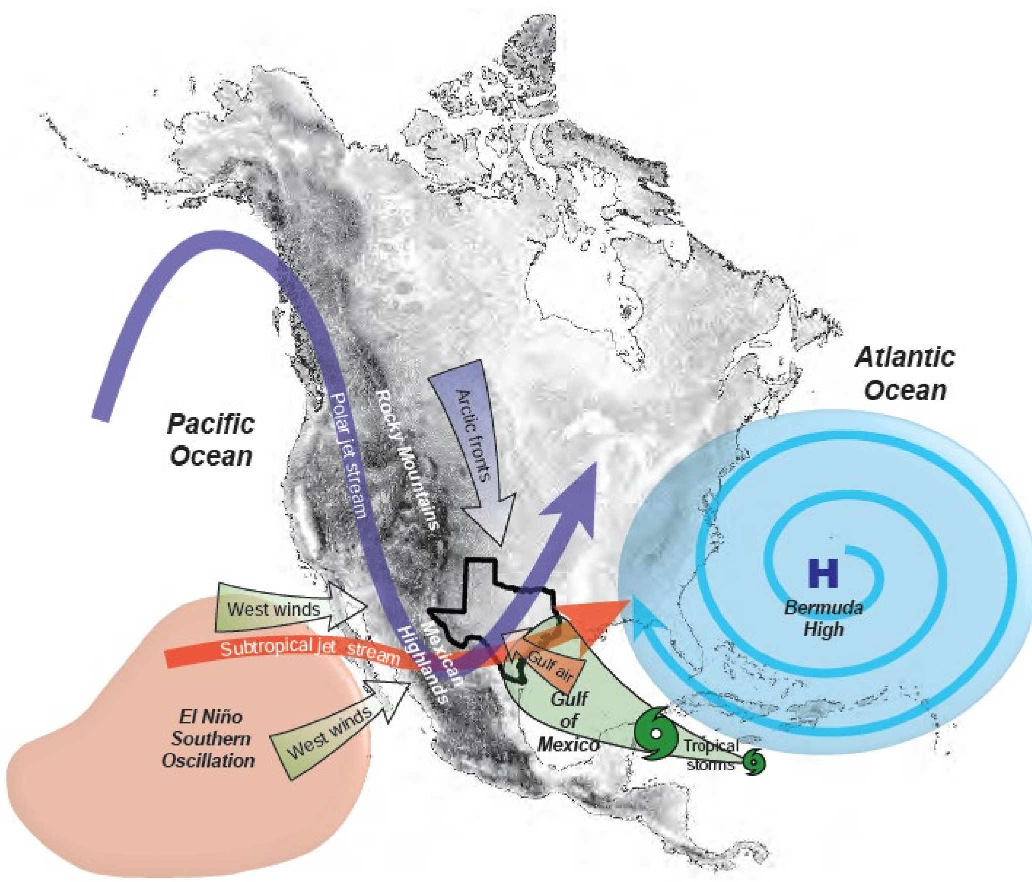

Figure A: Geographical Location of Texas Relative to Seasonal Air Masses

Precipitation in Texas is characterized by a profound east-to-west gradient. The average annual precipitation ranges from less than 10 inches in the arid western portion near El Paso to over 60 inches in the southeast portion near Beaumont (U.S. GCRP, 2018). Annual precipitation totals in the central part of the state vary from less than 20 inches to more than 60 inches from year to year (National Weather Service, 2024), where approximately half of the Texas population resides.

As illustrated in Figure B, Texas experienced an extremely active storm period between 2009 and 2020, with more than 20 storms exceeding infrastructure design levels. A similar active storm period occurred from 1930 to 1945. These storms provide a rich dataset for understanding the range of precipitation events likely to occur across the region. Understanding severe storms is critically important and this study attempts to better understand severe precipitation events and characterize them in ways that allow scientists and engineers to produce synthetic storms that accurately reflect storm potential across the region.

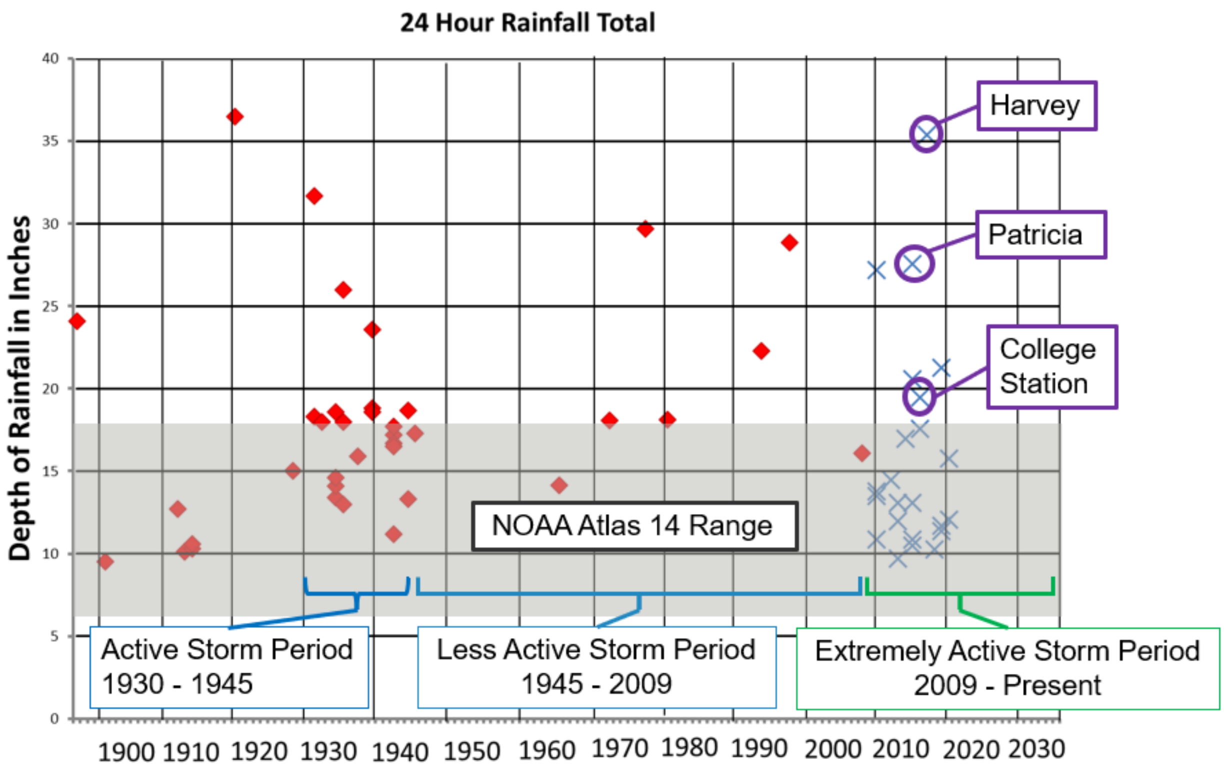

Figure B: Historical Timeline of Major Rainfall Events in Texas

(Note that this plot was made prior to the Texas Storm Study and does not adhere to strict geographical boundaries or robust rainfall data sources. However, it highlights an important point: Texas experiences notable wet and dry cycles that can drive large storms. The NOAA Atlas 14 box represents the 100-year, 24-hour precipitation depth for the Dallas-Fort Worth and the surrounding area.)

Previous flood-flow-frequency studies conducted by USACE have revealed that the climate variability in the central part of the state creates significant challenges for hydrologists in estimating flood-flow-frequency using flow observations alone. Lengthy dry or wet periods can cause significant shifts in flow-frequency determinations. It is not unusual for flow-frequency estimates, based solely on the observed annual series, to increase or decrease significantly with the addition of a couple of decades of data, even with 70+ years of record length, see Figure C.

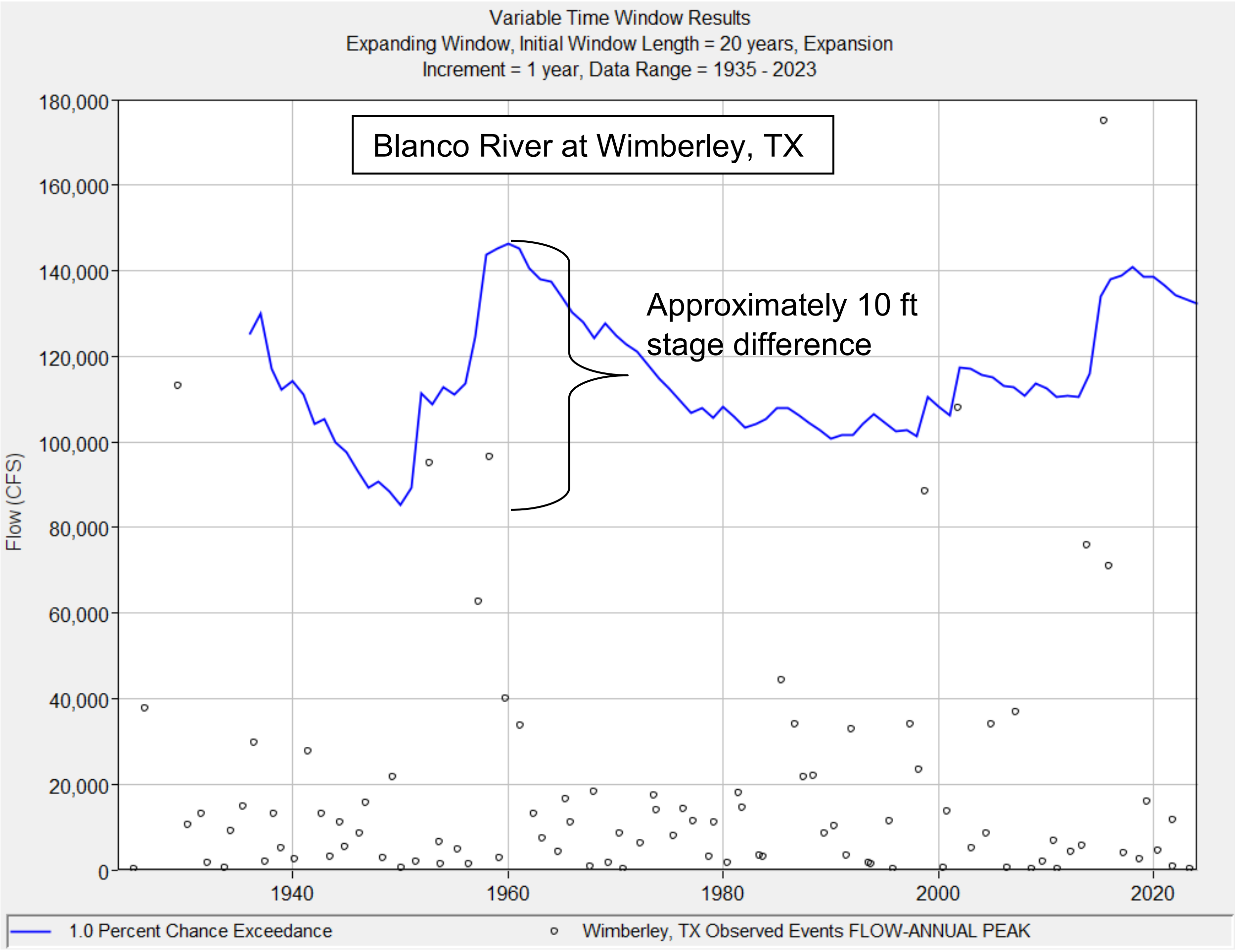

Figure C: Statistical Analysis of 100-year Peak Discharge at Wimberley, Texas

These shifts result in higher flood-flow frequency estimates after wet periods and lower estimates after dry periods. Therefore, it is necessary to employ design storms in rainfall-runoff modeling as a check against the annual series statistics and utilize more consistency in flood-flow frequency determinations. Design storms that accurately reflect the range of actual storms expected across the region also enable water resources engineers to accurately estimate peak discharges at un-gaged watershed locations.

This study represents a significant advancement in research supporting flood risk management and will be valuable for engineering practitioners and communities in reducing flood risk across Texas.

Executive Summary

Areal precipitation estimation is important in engineering design projects. Widespread and uniform precipitation has been conventionally used in hydrologic models to generate runoff from watersheds less than 400 square miles and no clear recommendations have been established for watersheds larger than 400 square miles or storm durations greater than 24 hours to date.

Recognizing this gap in knowledge and the strong need for better design recommendations for model-based peak discharge frequency analysis, the U.S. Army Corps of Engineers (USACE) partnered with the Texas General Land Office (TxGLO) and the Federal Emergency Management Agency (FEMA) to develop new design storm standard(s) that take into consideration new data and technology. That resulted in the Texas Storm Study (TSS).

The TSS goal was to analyze historic rainfall events and develop an updated design storm standard for use in model-based flood frequency analysis over large basins. The new standard is available and accessible to a broad range of engineering practitioners and was validated across multiple scales and basins.

The TSS scope of work included seven tasks: (1) Literature Review, (2) Data Collection, (3) Storm Analysis, (4) Regionalization, (5) DARF Verification, (6) DARF Database, and (7) Design DARF Curves. This document corresponds to the Task 7 deliverable and summarizes the work accomplished by the study and provides final recommendations for design. The report contains a summary of each TSS task. The full reports for each task are provided as appendices to this document.

As one of the main outputs of this study, updated DARF data for multiple durations (1-, 2-, 3-, 6-, 12-, 24-, and 48-hr) and annual return frequencies (1- to 25-yr, 50- to 200-yr, and 500-yr and beyond) and three relatively homogeneous DARF zones (East, Northwest, and West Zones) in Texas have been created and validated. Based on validation procedures, the updated curves correspond to the 50th percentiles DARF curves obtained based on the storm-centered storm-tracking methodology. To simplify the application of the data by practitioners, the final recommended curves are provided in a user-friendly web-based application called Interactive Texas Storm DARF Explorer (https://bit.ly/DARFtool[1]).

This report also provides a summary of recommendations for design storm methodologies and procedures and an example problem.

The TSS focused on providing guidance and standards for the development of elliptical design storms for use in model-based peak discharge frequency analysis over Texas for basins with drainage areas up to 10,000 square miles. This report concludes with a list of other methodologies to develop design storms that have been proposed and applied in the literature but were outside the scope of this study.

[1] Texas Storm Study - DARF dataset (arcgis.com)
https://www.arcgis.com/apps/dashboards/7a800ce84f424689955593fa88c42fe5

1. Background and Need

1.1. History

In the design of flood risk management projects, a commonly used method includes estimating the discharge for a specific return period and location by forcing a hydrologic model with a design storm with the same precipitation return period. This method, referred to as a model-based and probability-matching approach, requires hydrologic model calibration as well as meteorological assumptions about storms in the watershed of study. For small watersheds, it is generally acceptable to apply a uniform rainfall depth over the whole watershed at each time step. However, when watershed scales become relatively large compared to the scale of the real storms, uniformly applying the design rainfall depth over the entire watershed would produce unrealistic runoff. Historically, any watershed larger than a few square miles required a design storm with a reduction factor to account for the spatial variation in observed storms. For larger watersheds, especially ones larger than 400 square miles, more complex methods for design storms that consider the storm shape, size, and depth are needed for simulations to produce peak discharges reasonably consistent with the range of frequency peak discharges generated from statistical-based methods.

Historical design storm standards are limited to longstanding publications such as Technical Paper (TP) 40 (Hershfield, 1961) and TP49 (Miller, 1964), which were generated based on limited data and did not cover area sizes larger than 400 square miles. The U.S. Army Corps of Engineers (USACE), in partnership with the Texas General Land Office (TxGLO) and the Federal Emergency Management Agency (FEMA), felt the need to develop new design storm standard(s) that take into consideration new data and technology and that can better characterize the complex design storms needed to develop model-based peak discharges over large basins. Those standards are necessary to ensure that the results from single events and longer duration continuous simulations are consistent with frequency peak discharge results from statistical hydrology methods.

To address this challenge, USACE established a diverse team of experts from USACE, West Consultants, Inc, and researchers from the University of Texas at Arlington, Rice University, and Texas A&M University. The team was asked to collect and use storm parameters in conjunction with National Oceanic and Atmospheric Administration (NOAA) Atlas 14 (Bonnin et al., 2011) data to define design storms that are: (1) regionally appropriate and with physical characteristics observed in storms occurring across the region; (2) consistent with frequency precipitation depth/duration data as presented in NOAA Atlas 14; and (3) appropriate to be used for basins with drainage area up to 10,000 square miles. The deliverables of the Texas Storm Study (TSS) project will be used as guidance to generate synthetic design storms for future rainfall-runoff modeling studies and engineering designs.

1.2. Goals

The goal of the TSS is to analyze historic rainfall events and develop an updated design storm standard for use in model-based flood frequency analysis. The new standard should be accessible to a broad range of engineering practitioners and produce consistent results within basins and subbasins.

This project focuses on providing recommendations on design storms. Other relevant components of the model-based flood frequency analysis process, including the definition of initial conditions, model calibration, or storm optimization, are not discussed in this report.

1.3. Study Scoping

The TSS scope of work includes seven tasks: (1) Literature Review; (2) Data Collection; (3) Storm Analysis; (4) Regionalization; (5) DARF Verification; (6) DARF Database; and (7) Design DARF Curves. This document corresponds to the Task 7 deliverable which summarizes the work that has been accomplished by the TSS and provides final recommendations for design.

2. Summary of Work

The work accomplished in each task is summarized in this section. Detailed descriptions of each task are provided as appendices to this document.

2.1. Literature Review

The literature review had a broad scope, examining government publications and scientific journals, with subject matter related to design storms. Given many influential studies already published in this field of research, the literature review revealed the most glaring missing guidance in design storm methodologies relates to depth-area-reduction factors (DARFs). DARFs are used to convert point precipitation, like the one applied to generate NOAA Atlas 14, into areal precipitation over the area of interest, which is required for the **model-based peak discharge frequency analysis** for areas larger than a few square miles. To evaluate and improve the current DARF methodology, the TSS team conducted a thorough review of the existing DARF studies (100+) worldwide. The review first introduces the concept of DARFs with historical estimates of DARFs recommended for the United States. Historical design storm standards based on DARF curves were introduced in TP29 (U.S. Weather Bureau, 1957) and were later expanded on in TP49 (Miller, 1964). The review covers factors influencing DARF values and DARF methodology along with data requirements, storm characteristics, catchment characteristics, and methodologies for DARF determination.

Two methodologies are most often applied to estimate DARFs and were considered for this study: (1) fixed-geographic-area and (2) storm-centered approaches.

Fixed-geographic-area DARFs can be defined as the ratio between area and point rainfall with the same return period. Fixed-geographic-area DARFs have been criticized since they do not represent the spatial characteristics of observed rainfall events. On the other hand, this approach allows for the direct link between DARF and return period. However, recent literature shows no consensus about DARF dependency on return period. While some studies have indicated strong dependency (Bell, 1976; Skaugen, 1997; Sivapalan & Blöschl, 1998; Asquith & Famiglietti, 2000; Allen & DeGaetano, 2005; Veneziano & Langousis, 2005), others have argued against the existence or relevance of the dependency (NERC, 1975; Grebner & Roesch, 1997; Wright et al., 2014; Svensson & Jones, 2010). Fixed-geographic-area approaches tend to be more conservative (Svensson & Jones, 2010). The conservatism of the fixed-geographic area approach is demonstrated in the recent work of Kao et al. (2020). Kao applied watershed based fixed-geographic area approach for multiple regions in the USA. For the Texas-Gulf region for example, a reduction of approximately 10% was defined for an area of 386 square miles (1,000 sqkm), and a reduction of only 25% was defined for an area of 3,860 square miles (10,000 sqkm).

Storm-centered approaches of calculating DARFs determine the ratio between average depth of rainfall and the maximum point rainfall for a storm's areal extent (Geronimo, 2004, Olivera et al., 2006, Olivera et al., 2008, Curtis, 2013, Guo, 2012, Martins et al, 2014, Wright et al., 2014, Benson, 2014, Vieux, 2015, Hromadka et al., 2018; Thorndahl et al., 2019, Thomas, 2019, Hromadka et al., 2019, and InFRM, 2019). The main advantage of this approach is to capture the spatial variability of real storms. The main criticism arises from the fact that, in the past, this approach focused on a limited number of storms. With the advance of new technology and long-term gridded rainfall datasets, this approach can be applied probabilistically if many storms are included.

Storm-centered approaches can be based on fixed boundary or storm-tracking approaches. Fixed boundary DARFs are calculated based on an area (spatial boundary) that is fixed through time. The boundary can be a watershed or the area of maximum rainfall for a specific event. Storm-tracking approaches track the movement of the storm, and the area of interest moves as the storm moves. A schematic representation of the approaches, together with a summary of the advantages and disadvantages of each approach are shown in Figure .

Scientists and practitioners do not fully agree on which approach is the best for model-based frequency analysis. Therefore, the team met multiple times during this study to deliberate the advantages and disadvantages of each approach and to determine which approach is most appropriate for this study. Since the goal is to generate realistic design storms, the team decided on the storm-centered approach, which captures the spatial distribution of historical events. While applying this approach, many storms were evaluated with the goal of providing a probabilistic, rather than deterministic, characterization of storm spatial distribution. With the application of the storm-centered approach, the team was also able to extract other relevant storm parameters, including storm size, direction, speed, and angle.

For more details on the DARF methodologies, please refer to Appendix 1.

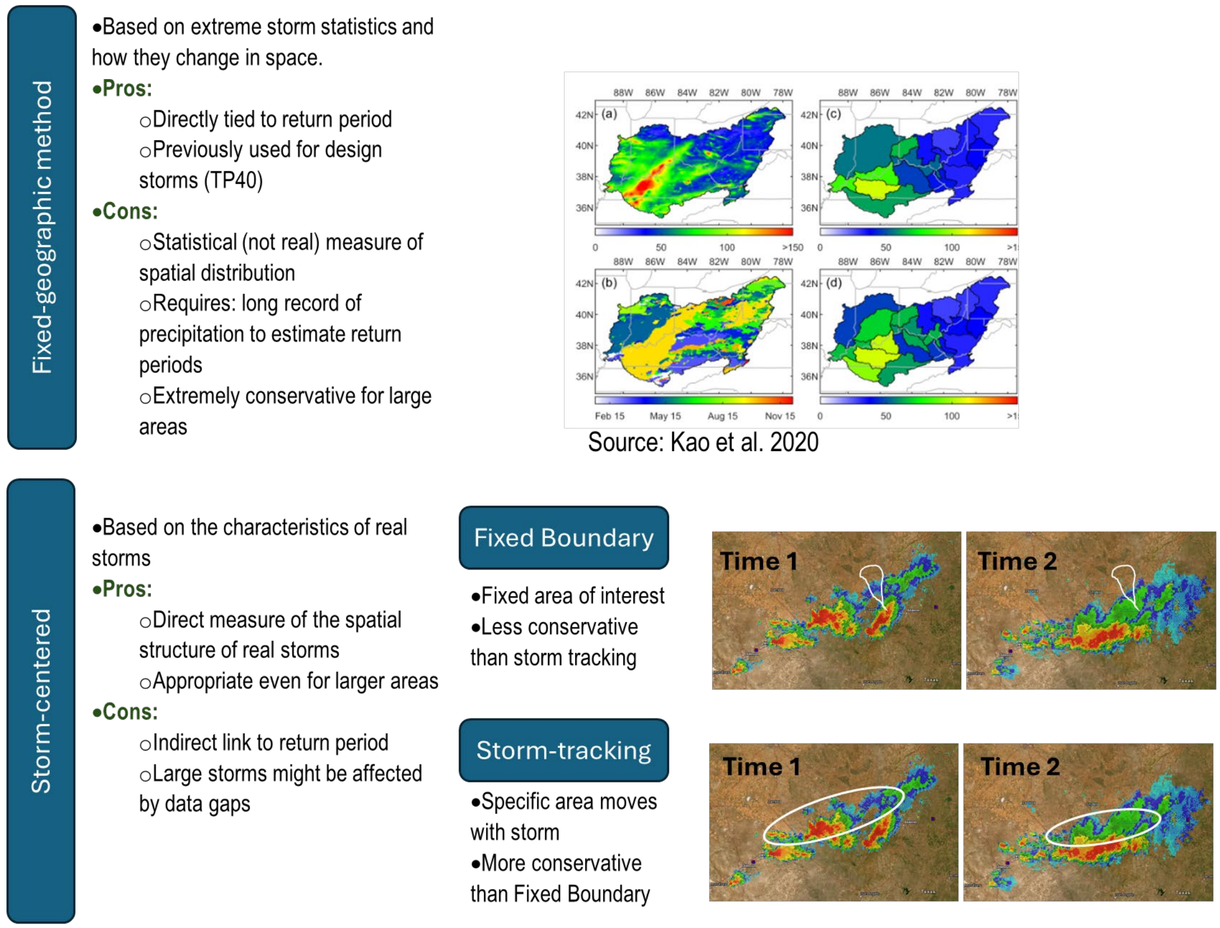

Figure 1: DARF methods considered in this study with highlighted advantages and disadvantages for the broad categories: (1) Storm-centered and (2) Fixed-geographic

2.2. Data Collection

Task 2 of the TSS focused on collecting and evaluating different rainfall datasets to determine the most appropriate datasets for the analysis. Multiple point (gage-only) and gridded (either gage and/or radar-based) rainfall datasets were collected and analyzed. Based on the evaluation of the point (gage-only) datasets, the team concluded that the density of the available rain gage network is not high enough across all areas of the State to resolve the spatial variability of storm events, especially for convective storms and older events. If point gage data were used, the storm selection procedure would be limited to the most recent period of record, when gage density is higher, and more gages present high-resolution temporal data (hourly). The team concluded that the analysis should generally focus on gridded rainfall products, which in many cases combine gage and radar rainfall (e.g., multi-sensor products).

Table 1 includes general characteristics for the multiple gridded datasets collected and evaluated in Task 2, including spatial and temporal resolution, source data, and period of record.

Table 1: General characteristics of gridded datasets

Gridded Product	Spatial Resolution	Temporal Resolution	Source Data	Period of Record
AORC	4 km x 4 km	Hourly	Gage, radar, and satellite	1979 to near present
MRMS Archive	~1 km x 1 km	Hourly	Gage, radar, and satellite	2015 to present
MRMS Reanalysis	~1 km x 1 km	5-min	Gage, radar, and satellite	2001-2011
Stage IV	~4 km x 4 km	Hourly	Gage and radar	2002 to present
IEM Mosaic	1 km x 1 km	5-min	Radar	1995 to present
PRISM	4 km x 4 km	Daily	Gage and radar	1981 to present
RFC MPE	2 km x 2 km	Hourly	Gage, radar,	2004 to present
Livneh	6 km x 6 km	Daily	Gage	1915-2011
Daymet	1 km x 1 km	Daily	Gage	1980-to present

Note: for detailed information on each dataset refer to Appendix 2.

The following conclusions were drawn from the analysis:

Except for the western corner of the State and a few limited areas in the eastern and southern regions, Texas has good radar coverage.

Multiple gridded rainfall products are available for the State. The products vary in terms of the methods and data used, spatial and temporal resolution, and period of record. The Analysis of Record for Calibration (AORC) dataset presents the longest period of record (1979 to 2020) for hourly data, while Multi-Radar/Multi-Sensor System (MRMS) and Iowa Environmental Mesonet (IEM) Mosaic present the highest temporal (5-min) and spatial (1-km) resolution.

The Parameter-elevation Relationships on Independent Slopes Model (PRISM) and the AORC datasets are based on both radar and gage data. Because they applied radar data that had previously undergone quality control, PRISM grids have been corrected for beam blockage and other artifacts of radar data.

Different data products present varying depictions of the same events, even when the data products were drawn from similar sources. Figure 2 shows the different depictions of Hurricane Harvey, based on the seven data products that include radar (with or without bias correction) as a source. Depictions of the April 2011 convective storm also varied between the seven radar-informed datasets (see Appendix 2). The suitable dataset thus depended on the intended application; namely, what spatiotemporal resolution and period of record were needed for certain analysis and types of storms, as discussed later.

The AORC dataset provides a few advantages over the other gridded datasets, including having a longer period of record (1979–2020) and the availability of hourly data. The AORC uncertainties vary significantly for different years and regions. This limitation was acknowledged by the team and was taken into consideration during the analysis.

While the AORC dataset is appropriate for large-scale storms, it is not recommended for convective storms due to the coarse spatial resolution.

The Livneh dataset is recommended for analysis that does not require hourly data and that requires longer periods of record. Two versions of the Livneh dataset are available: split (divides the daily gage values into two days) and unsplit (does not divide the gage daily value to maintain daily peaks). While the split version was applied in this report, for additional tasks in this study the use of the unsplit Livneh dataset is recommended since it would lead to more conservative results.

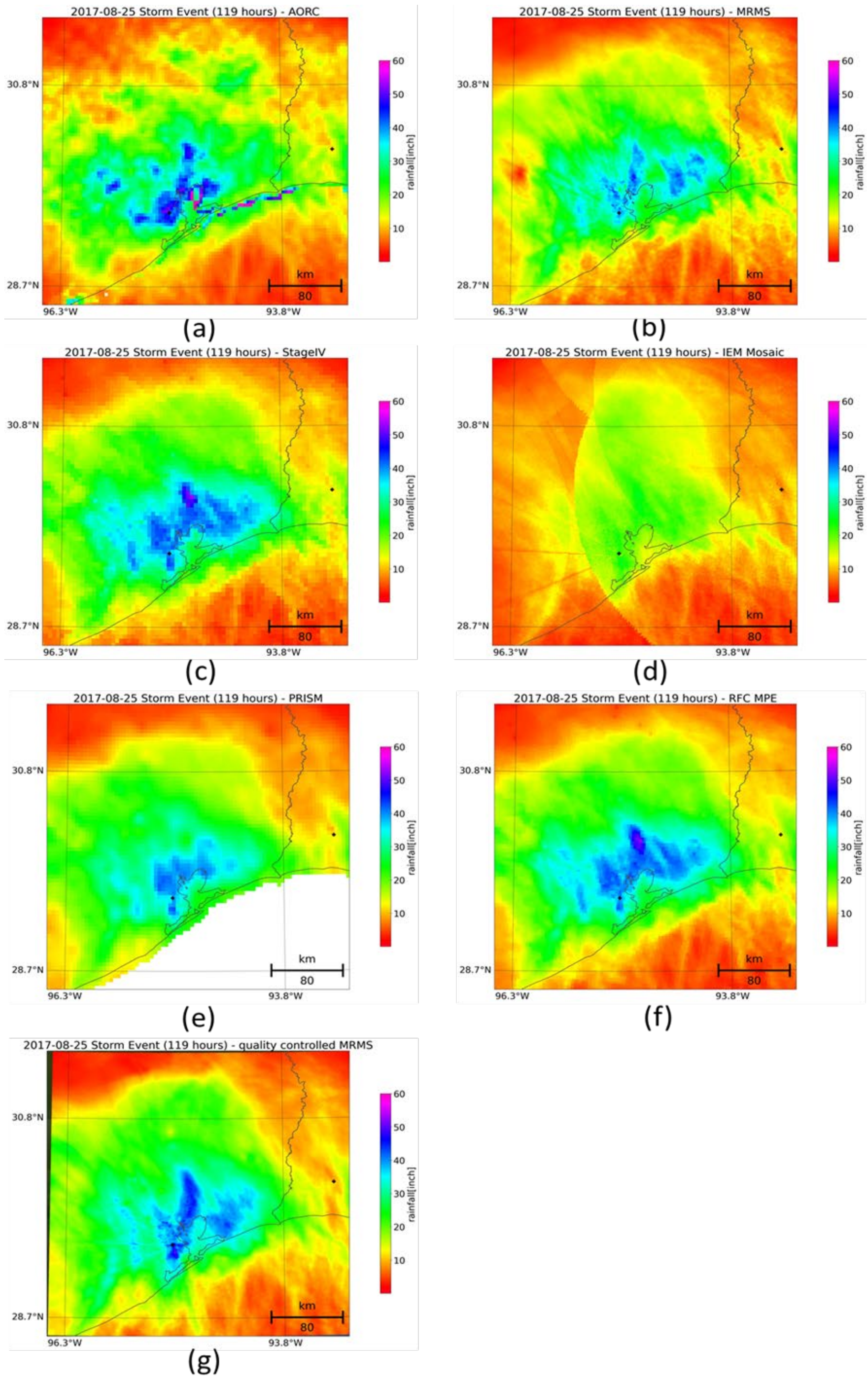

Figure 2: Hurricane Harvey (August 25th–29th 2017) total rainfall map based on (a) AORC, (b) MRMS, (c) Stage IV, (d) IEM Mosaic, (e) PRISM, (f) RFC MPE, and (g) quality controlled MRMS datasets

A parallel DARF study for Arizona (Flood Control District of Maricopa County, 2021) evaluated DARF extracted based on the AORC, IEM, and a proprietary higher resolution bias-corrected dataset (Storm Precipitation Analysis System (SPAS), which is not included in this study). The study concluded that, for convective storms, DARFs extracted based on the IEM and the higher resolution bias-corrected dataset were very similar in shape, while the DARF based on the AORC dataset was more conservative because of its coarser resolution. The AORC grids produce a very good match to the SPAS high-resolution DARFs for larger scale and longer duration events.

Based on the analysis performed for Task 2 and the conclusions from the Arizona study, AORC grids are recommended for synoptic scale type of storms (e.g., fronts and hurricanes), while the IEM grids are recommended for mesoscale local storms (e.g., thunderstorms). The unsplit Livneh dataset is recommended for analysis that does not require hourly data but does require longer periods of record. These datasets were adopted for the DARF analysis (Task 3).

For more details on the data collection methodologies, please refer to Appendix 2.

2.3. Storm Analysis

Task 3 of the TSS presents an extensive analysis of storms in Texas. Historic rainfall events were analyzed with the goal of extracting relevant storm characteristics that can be applied to constructed design storms. The information provided in the Task 3 of the TSS is used as the main input to Tasks 4, 5, and 6.

Four groups of storms were evaluated: (1) Statewide Heavy Precipitation Events; (2) Idealized Boundary Precipitation Maximization Events; (3) Convective Storm Events; and (4) Multi-Day Precipitation Events. Detailed information on each of the groups is provided in Table 2. Each group includes many storm events that were selected based on different storm characteristics (e.g., intensity, coverage, type).

Storm events in Table 2 are defined by a location with boundary coordinates and a distinct start and end time. Storm cells are representations of independent spatially and temporally continuous storms that can be tracked to extract additional characteristics like storm movement. Within a storm event, multiple storm cells can be identified and tracked. Storm events are characterized by their size, intensity, and DARF. Storms cells are characterized by their size, shape, intensity, temporal distribution, movement (direction, speed, angle), and DARF. Multiple storm cells can be identified during a single storm event. More details on the event selection criteria specified in Table 2 are provided in Appendix 3.

Table 2: Storm event groups

ID	Name	Description	Type of Storm Characterization
1	Statewide Heavy Precipitation Events (SWHP)	Attempts to capture large and intense mesoscale events that might have covered large areas of the State.	Storm cells
2	Idealized Basin Precipitation Maximization (IBPM) Events	Identify specific storm events that created large rainfall volumes over areas varying from 400 to 40,000 square miles).	Storm events
3	Convective Events	Focus on identifying convective storms by applying thunderstorm warning and observation records.	Storm cells
4	Multi-Day Precipitation Events (MDP)	Identifies long-duration ($\geq 2\ day$) precipitation events affecting major Texas watersheds. This is a supplementary dataset for Group 1, increasing the sample size for long-duration DARF curves.	Storm cells

The remaining tasks in this study apply data from storm event Groups 1 and 4. Storms in Group 1 were selected using the AORC dataset focusing on storms with relatively high intensity that cover large areas (See Appendix 3 for details on event selection). A total of 431 storm events were selected, including major storms like tropical storms Imelda, Gordon, and Fay and Hurricanes Harvey and Ike. From these storms, 19,252 individual storm cells were tracked and analyzed for DARF and other properties like storm speed, shape, direction, and intensity. Group 4 supplements the Group 1 dataset's DARF sample size for durations greater than or equal to 2-days. Group 1 and 4 events span March 1979 – November 2019.

Groups 2 and 3 were not used for Tasks 4 through 6. Group 2 presents DARFs extracted using a fixed boundary instead of the storm-tracking approach. In this approach, a polygon is defined with a certain size and shape over an area of higher return period precipitation, and DARFs are extracted over that specific polygon. This method resulted in less conservative DARFs. Moreover, DARFs were generated only for durations larger than 2-days since the method used unsplit Livneh data instead of AORC data. Group 3 was analyzed to provide information for small-scale convective storms. Ultimately, however, small-scale storms are not the focus of this study.

The storm cell tracking method adopted for Groups 1 and 4 allowed the team to extract other relevant characteristics for storms in Texas, some of which are discussed herein. For a complete list of variables extracted, please refer to Appendix 3. Figure 3 shows vectors with the start and end position of each storm cell tracked in Group 1 for different storm durations. Note that additional long-duration (≥ 2 days) storm cells were extracted in Group 4 but are not shown in Figure 3 or the statistics in Figure 4 and Figure 5. (More information on Group 4 storm characteristics can be found in Appendix 3). Storm cell density is relatively uniform across the State at lower durations. However, for longer durations, areas in northeastern Texas and along the Gulf of Mexico have greater storm cell density, as expected from wetter eastern Texas climatology.

Figure 4 (left) shows storm cell duration distribution (median of 8-hr). The longest storm cell duration tracked was 169-hr, or approximately 7 days, for Hurricane Harvey (2017). Figure 4 (middle) shows yearly distribution of storms. Note that a larger number of storms were identified after 1996, when NEXRAD weather radar data became available. That is likely, at least partially, an artifact of the data. Figure 4 (right) shows the total storm area, with median area of approximately 19,195 square miles.

Tracked storm travel angle and speed distributions are also shown in Figure 5. Most storms have average travel speeds within 13 to 27 mi/hr (21 to 44 km/hr). Storm cells within the sample of tracked storms favor southeast, east, and northeast travel directions, with travel angles between -60 to 60 degrees counterclockwise of due east. Figure 5 shows travel angles as a function of duration. As duration increases, storm cell travel increasingly favors the northeast direction.

The Task 3 TSS report (Appendix 3) also evaluated properties (aspect ratio, area, and ellipse angle) of fitted ellipses at 60-min timesteps. See Appendix 3 for more details. This dataset is key for the generation of realistic dynamic storms, which is outside of the scope of this study.

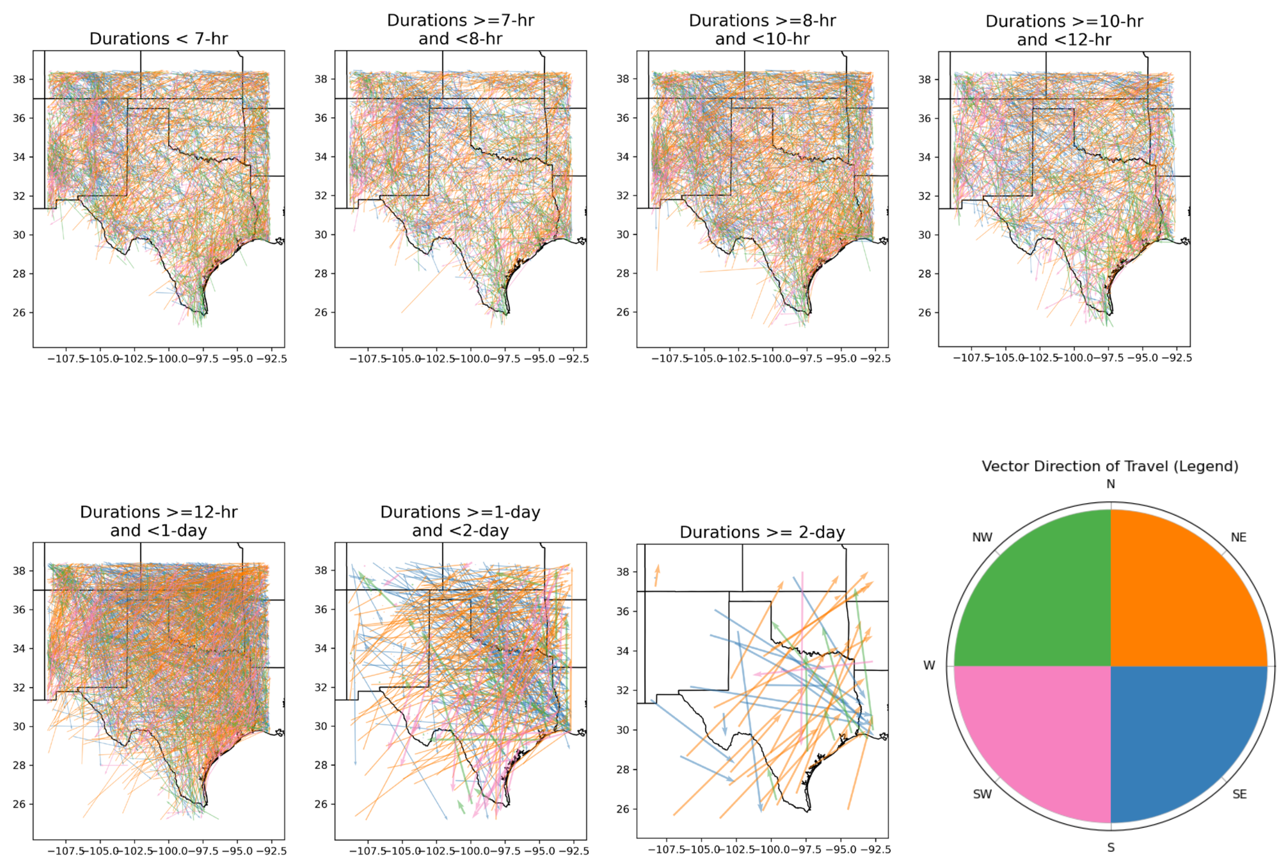

Figure 3: Storm vectors for all tracked storm cells, separated by duration. Vectors point from the storm's starting to ending position and are color coded by travel angle

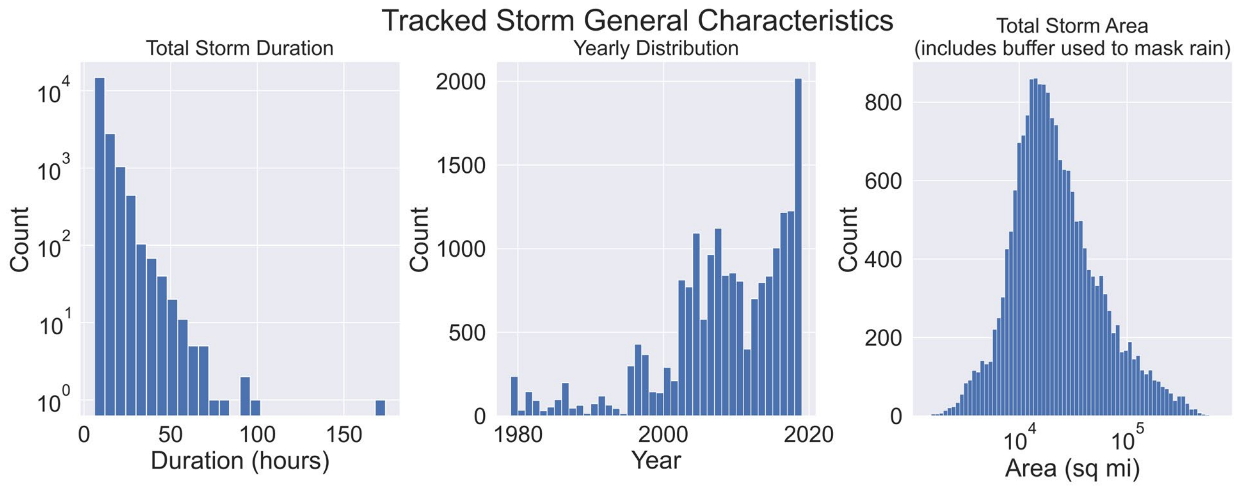

Figure 4: Distribution of characteristics of tracked storms including total storm duration (left), year of occurrence (center), and total storm area (right)

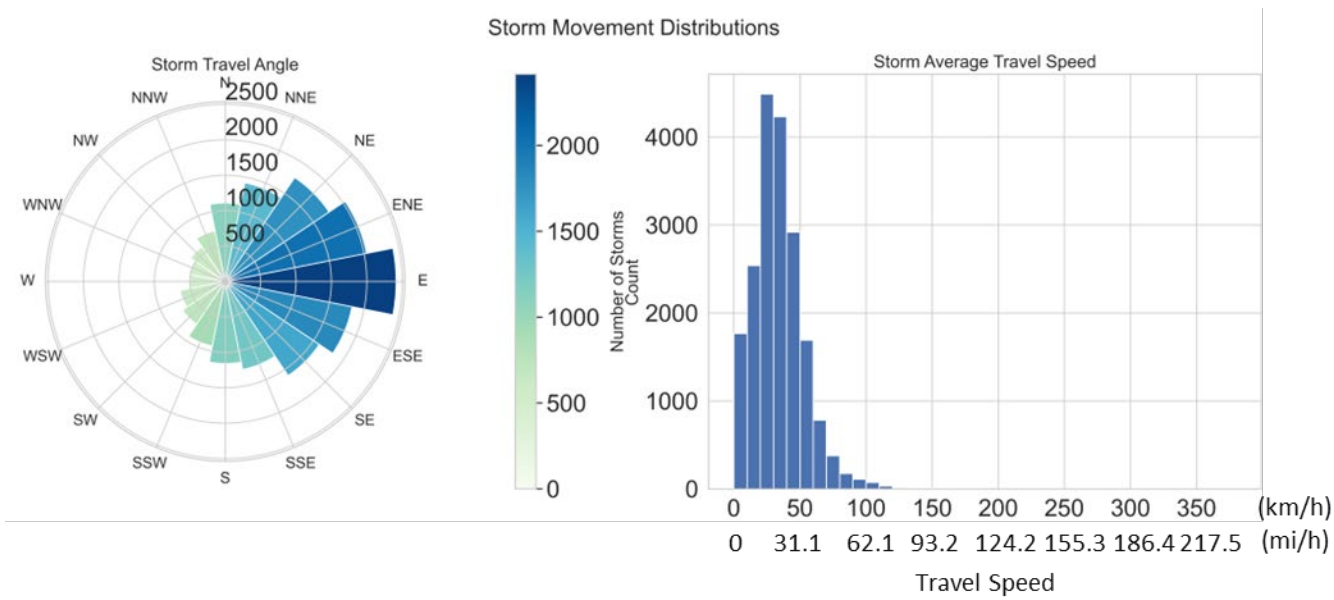

Figure 5: Distribution of storm travel angles (left) and average travel speed (right) for all tracked storms

Finally, DARFs were extracted for Group 1 and 4 storm cells and characterized based on their approximate return periods. DARF return periods are approximated based on the highest point rainfall magnitude used in the DARF curve, relative to NOAA Atlas 14 Precipitation Frequency Estimate precipitation values at the same location. Different groups of return periods were defined with the goal of obtaining an adequate sample for each group. An example of DARF curves classified by return period is provided in Figure 6 for the 1-day duration. Note that the figure includes the 5th, 50th, and 95th percentile for each class of return period. For all other durations, please refer to Appendix 3.

As shown in Figure 6, the 50th percentile DARF tends to be less conservative (greater reduction) as the return period increases. However, quantifying this relationship would require a larger sample of storms with return periods greater than 100-yr, which was unavailable, even with the long period of record (~38-yr) applied in this study. Section 3.4.3 discusses how DARF curves for various return periods were grouped so robust sample sizes inform design curves.

The data generated by this task were applied in Task 4 to determine DARF zones, and the final DARFs used in the TSS are zone dependent.

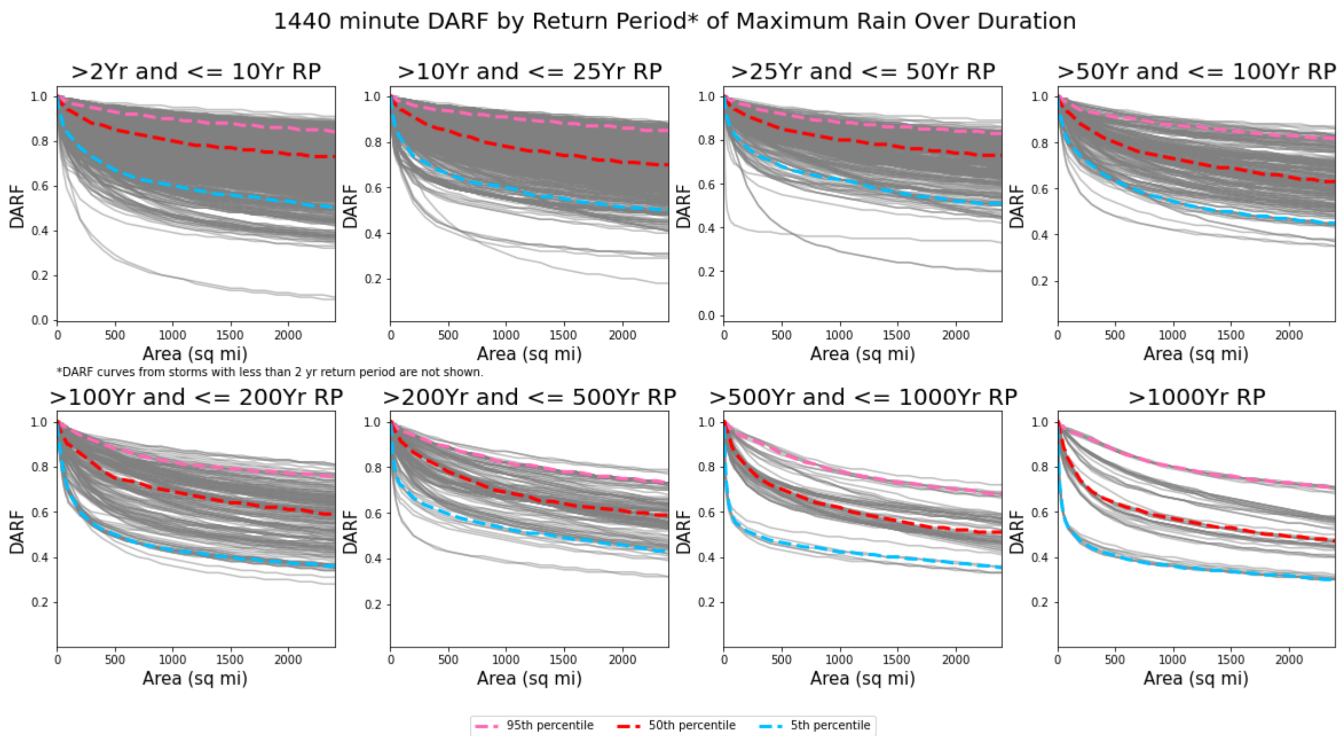

Figure 6: 1-day DARF curves, sorted by approximate return period

2.4. Regionalization

Task 4 of the TSS focused on identifying regional differences in storm characteristics and temporal changes in storm intensity. For more details on the analysis please refer to Appendix 4.

2.4.1. Regionalization

Regional differences in DARFs, DARF ratios, storm orientation, and storm motion were considered, using two sets of data from Task 3. The first set was storm-tracking output from high-precipitation Texas weather episodes using the AORC gridded dataset for 2002–2019 (Group 1). The second set was DARF information for multiday storms identified from the Livneh dataset (Group 4).

The shape of the DARF curves (as measured by the value of the DARF at an area size of 400 sqmi) differed considerably across the state of Texas (see Figure 7). In Colorado, New Mexico, and far west Texas, precipitation decreased by area, making a typical value of the DARF smaller when compared with other areas included in Figure 7. In other words, precipitation tended to drop off rapidly from the storm center, leading to smaller amounts overall. Other similar reductions in DARFs along other boundaries are attributed to interference from the lateral boundaries, which forces the storm intensity to drop off more rapidly with latitude because part of the intense storm is missing. Those boundaries in data collection were sufficiently far from Texas and its watersheds so that storms statistics within those regions are unaffected, except along the coast where data far enough offshore was unavailable.

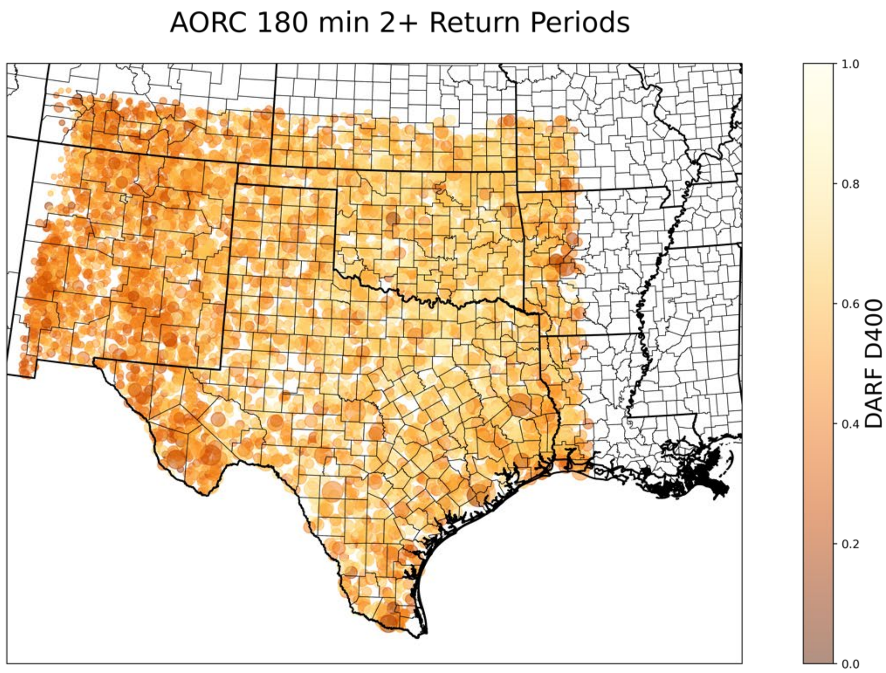

Figure 7: Depth-Area Reduction Factors at 400 sqmi (DARF D400) for all 180-min storms with at least a 2-yr return period

There was no clear spatial pattern to storm orientation. The predominant orientation of the storm ellipse major axis was east-northeast to south-southwest. Relatively few storms were oriented northwest to southeast, the typical orientation of moderate to large rivers in the State. There were large variations in storm motion (see Figure 8), certain spatial patterns emerged. Most prominent pattern was a tendency for storms in most of Oklahoma, the Texas Panhandle, and adjacent parts of Texas to move eastward at speeds more than 10 mph. This difference was sufficiently prominent that it became the basis for one of the homogeneous zones.

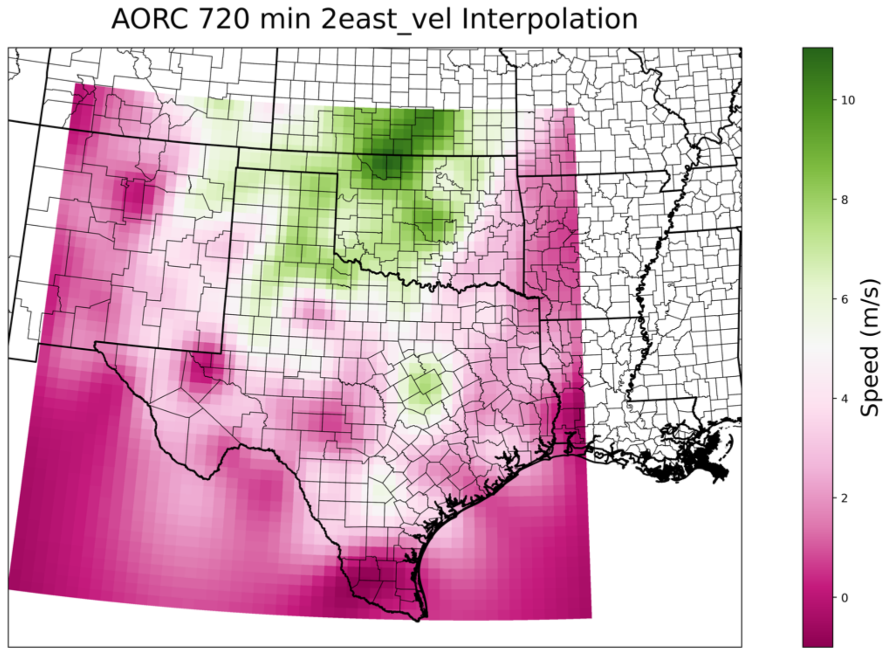

Figure 8: Eastward component of storm motion during 12-hr period, 2-yr and larger storms

There was a tendency for storms with higher return periods to have slightly smaller (less conservative) DARFs at standard sizes such as 1,000 square miles, 3,000 square miles, and 10,000 square miles. Results for 3,000 square miles and multiple return periods are shown in Figure 9, where the x-axis shows different return periods from 2- to 1,000-yr and the y-axis shows DARF for a 3,000 square miles basin (D3000). This is interpreted to mean that storms with a given rate of precipitation production produce greater local precipitation totals if they move slowly, and the highest return period storms have both large precipitation production and slow movement.

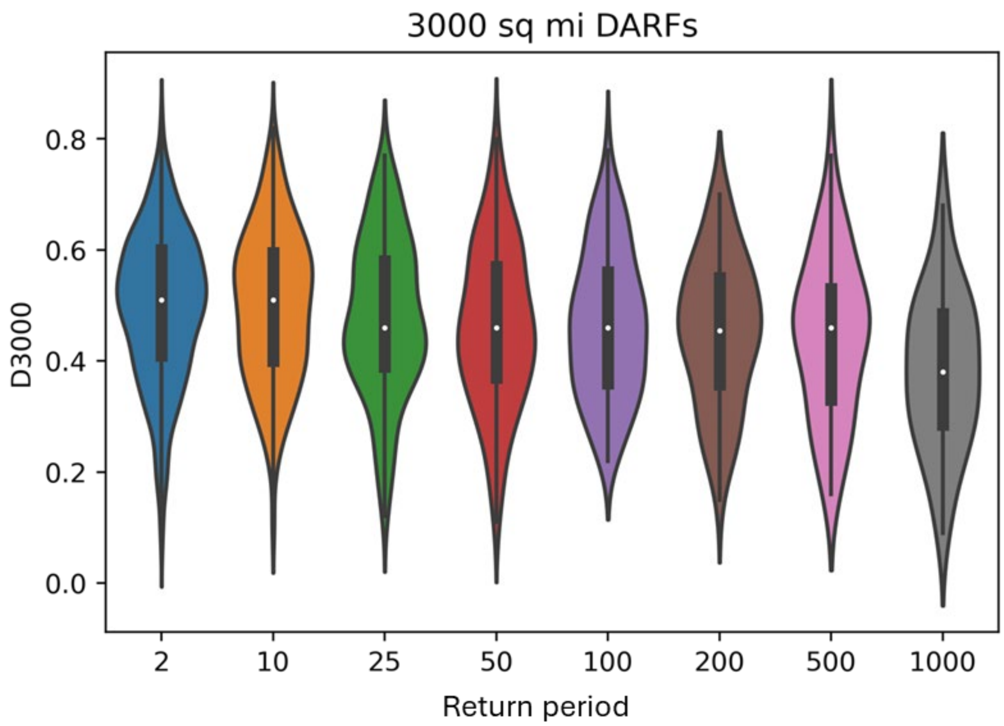

Figure 9: DARF for a 3,000 sqmi basin for return periods varying from 2- to 1,000-yr

Based on these analyses, subdivision of the State of Texas and surrounding areas into three relatively homogeneous zones was recommended. The largest zone includes the bulk of Texas, within which DARF shapes as well as other key storm characteristics such as storm translation speed and direction showed no consistent geographical variations. A separate coastal zone was considered and rejected, as no clear differences in storm metrics were found there compared to storms farther inland. A second zone, representing faster-moving storms, occupies much of northwest and west-central Texas. The third zone includes New Mexico, far west Texas, and much of northern Mexico. The original estimated boundaries of these zones (green) were then adjusted for operational purposes to coincide with river basin margins. Figure 10 shows the final Texas DARF homogeneous zones.

Storm transposition boundaries were not investigated in this study. However, the following recommendations are provided solely based on the team's combined expertise and experience, together with the results of the analysis on the shape, DARF, and motion of storms (not intensity): (1) in any storm transposition, the climatological variations in normal and extreme rainfall should be respected (2) storm can be more freely moved (up to 150 mi) within any specific zonal boundary, (3) storm transposition distances across zonal boundaries should be small and investigated on a case-by-case basis.

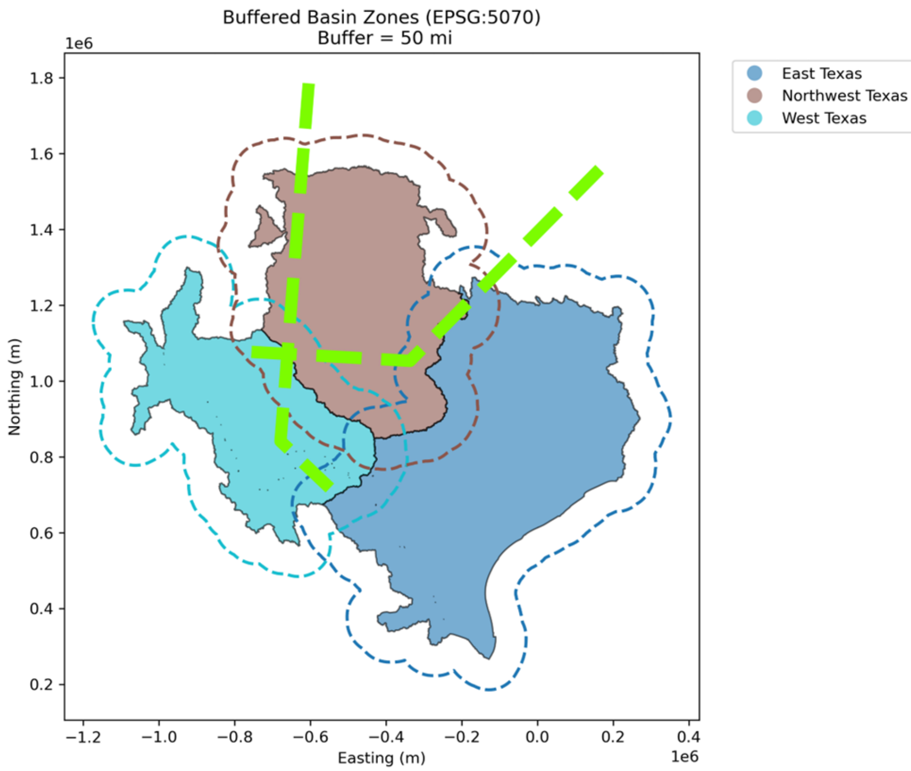

Figure 10: Texas DARF homogeneous zones with a 50-mi buffer with green-dashed lines showing original boundaries considered at the beginning of this study

2.4.2. Trends in Extreme Rainfall

Statistically significant trends in extreme rainfall are found in historical observations, historical gridded analyses, statistically downscaled global climate model (GCM) outputs, and dynamically downscaled GCM outputs. The analysis in this study of GCM historical simulations and projections downscaled to major river basins in Texas finds trends on the order of 10% per half century, larger for more extreme rainfall values and relatively short durations. A recent analysis of observations (Jorgensen and Nielsen-Gammon) finds similar trends. Because of natural spatial variability in extreme weather, variations within Texas of the extreme rainfall trends are not expected to be robust compared to the overall regionwide trends. These results partly justify the need to develop widely accepted methods for incorporating climate-driven nonstationarity into flood risk analysis.

2.4.3. Recommended DARFs by Zone

DARF curves were classified based on return period groups and the three zones in Texas with similar storm properties. DARFs for different return periods were grouped to ensure robust sample size for each return period grouping and used to calculate design curves for modeling of frequent events (2- to 50-yr return periods), events bordering 100-yr return period (50- to 200- yr return periods), and very infrequent events (greater than 200-yr return period). The final 50th percentile curves are shown in Figure 11 for the East Texas Zone, Figure 12 for the Northwest Texas Zone, and Figure 13 for the West Texas Zone. The sample size of 2,880-minute DARF curves was more limited than other durations, especially in the Northwest and West Zones. After extensive discussion, 2,880-minute DARF curve recommendations are based on 2,880-minute DARFs from any zone but are only recommended for use in East Texas.

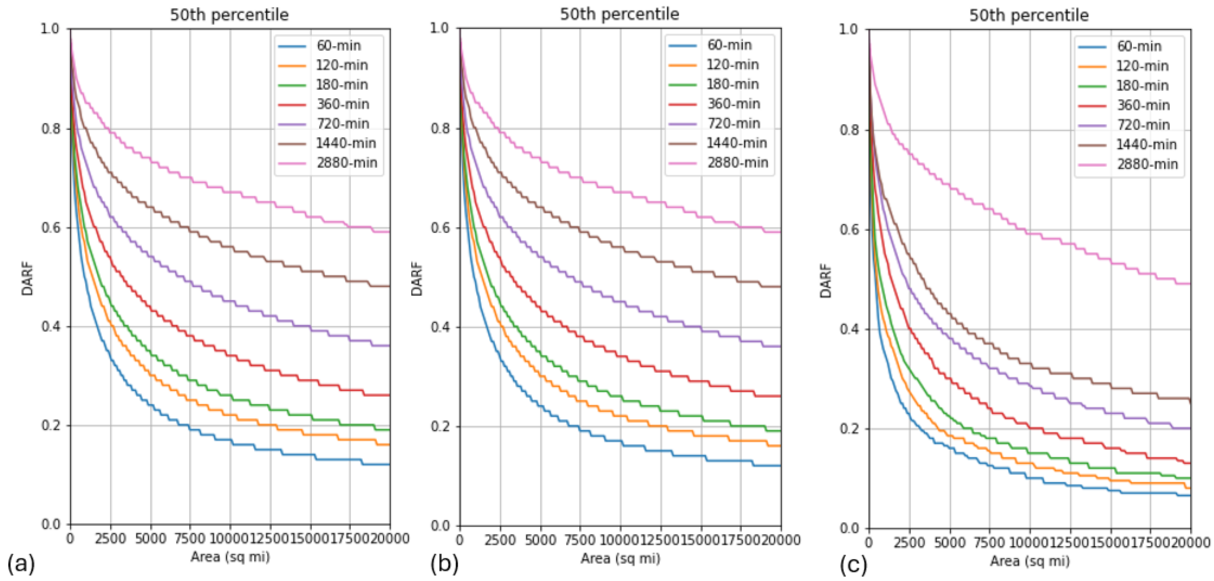

Figure 11: East Texas design DARF curves for (a) 2- to 50-yr (b) 50- to 200-yr; and (c) above 200-yr return periods

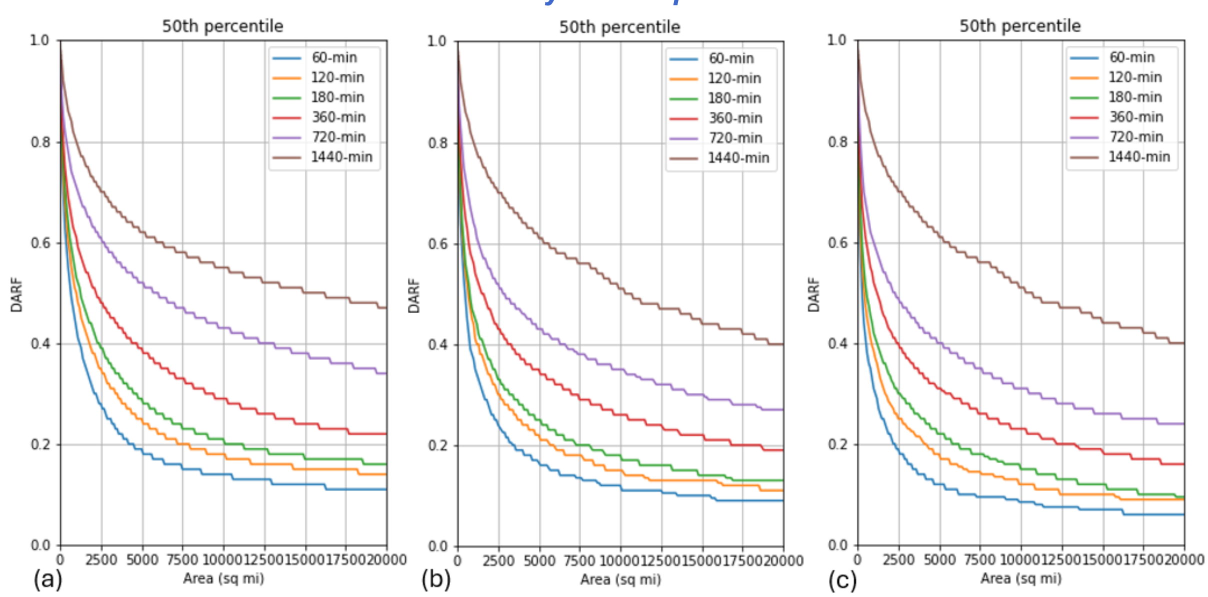

Figure 12: Northwest Texas design DARF curves for (a) 2- to 50-yr; (b) 50- to 200-yr; and (c) above 200-yr return periods

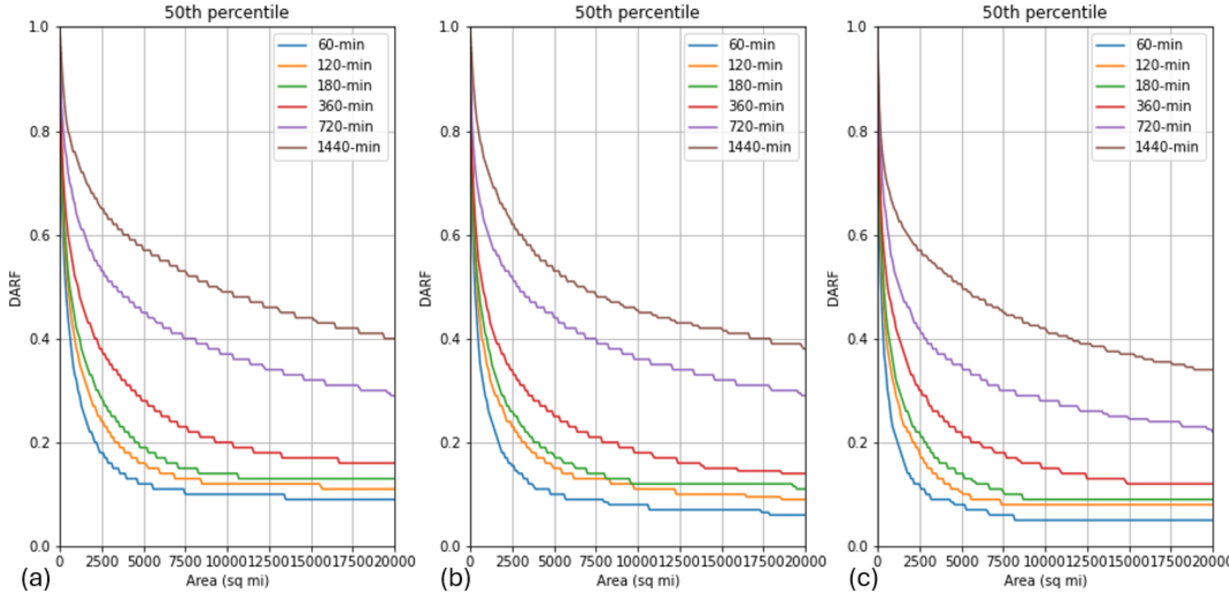

Figure 13: West Texas design DARF curves for (a) 2- to 50-yr; (b) 50- to 200-yr; and (c) above 200-yr return periods

2.5. Validation of DARF Curves

2.5.1. Validation for Trinity and Neches

Task 5 had two primary goals. The first was to validate the DARF curves generated in this study. The second was to define the DARF curve percentile most appropriate to generate design storms consistent with other methods and results (i.e., statistical-based approaches and previously published reports that applied the model-based approach). To verify that the recommended DARFs would provide reliable results when used within the design storm framework for a discharge frequency estimation, there was a need for highly calibrated, reliable hydrologic models as well as thorough investigation of the annual peak discharge statistics. This limited the ability to verify the DARFs as not all Texas watersheds have such hydrologic models readily available. For the model-based approach, the Watershed Hydrologic Assessment (WHA) studies published by the Interagency Flood Risk Management (InFRM, 2021) team were used as baseline. These studies provided high quality hydrologic models coupled to basic statistical guidelines for site-specific frequency (Bulletin 17C analyses).

The DARFs generated based on Tasks 3 and 4 were applied to build elliptical design storms. The same ellipse ratio and orientation from InFRM (2021) were adopted. These were then used as inputs to the previously calibrated hydrological model. Peak discharges were simulated for multiple return periods and multiple locations over the selected watersheds. Figure 14 showcases the InFRM hydrologic models over Texas that have been previously used in large-scale storm design studies using DARF. For this study's purpose, two major watersheds, Trinity and Neches, were picked to validate the DARF curves.

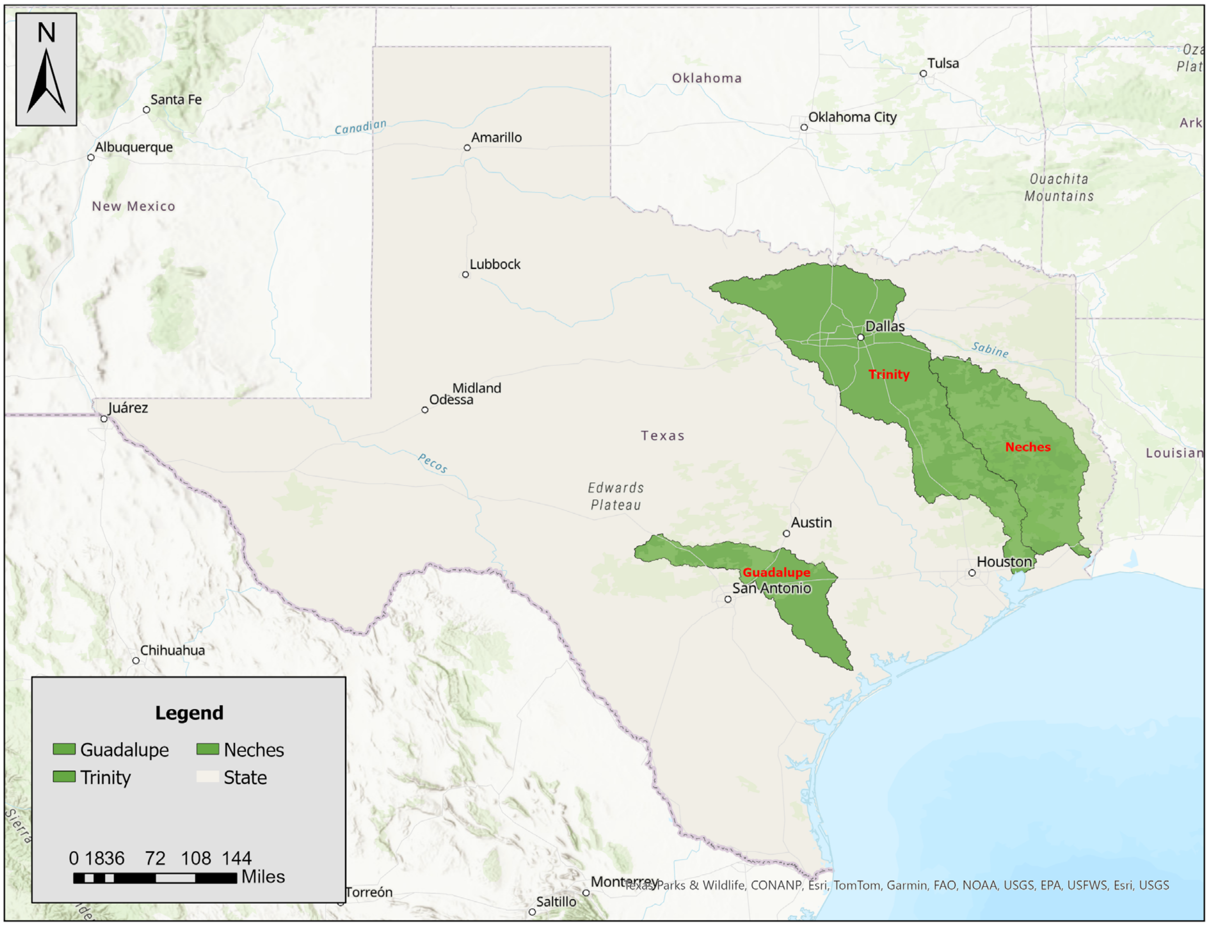

Figure 14: InFRM hydrologic models over Texas that have been previously used in large-scale storm design studies using DARF: Guadalupe, Trinity, and Neches River Watersheds

Another outcome from this task was a streamlined automated procedure to prepare the required datasets for the simulations, run the model, and process the outputs. A schematic workflow of all the steps required to run the model is shown in Figure 15. The procedure includes five steps:

1. Develop elliptical design storms with DARFs;
2. Extract design rainfall values from NOAA Atlas14 over individual watersheds with the elliptical storm from Step 1;
3. Prepare the hydrologic model (HEC-HMS) based on the information required for each specific return period. Initial soil conditions were determined based on the recommendations provided by the WHA studies;
4. Automate the hydrologic simulations based on the various DARF percentiles and HEC-HMS junctions; and
5. Extract the simulated results and compare with the published WHA results and the

Bulletin 17C statistical results for the locations of interest.

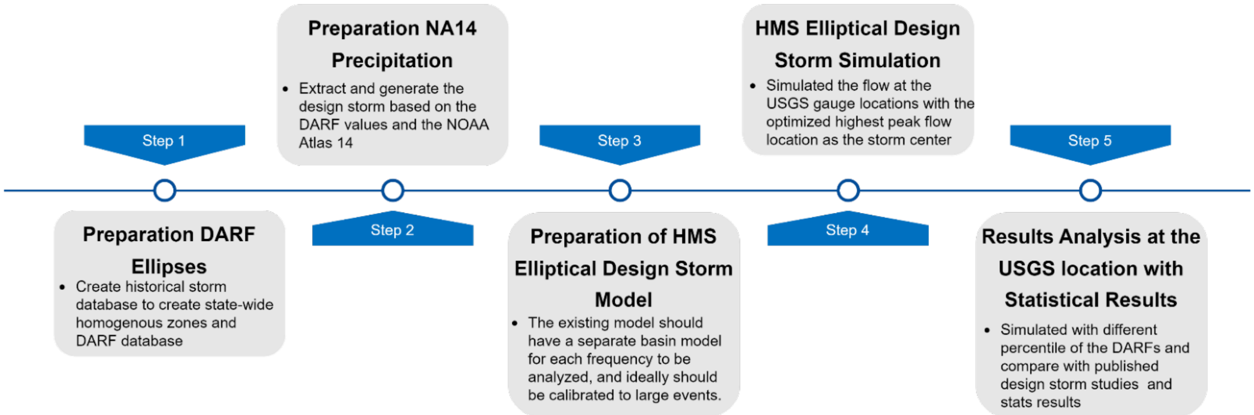

Figure 15: Schematic workflow of all the steps required to run model-based peak discharge frequency analysis based on elliptical design storms

Recommended DARFs are classified based on three return period groups (1- to 10-yr, 25- to 200-yr, 500-yr and beyond), multiple durations (1-hr, 2-hr, 3-hr, 6-hr, 12-hr, 24-hr, 48-hr, 72-hr, and 96-hr), and three zones in Texas (East, Northwest, and West Texas).

While results were generated for multiple durations and return periods, the 10-yr and 100-yr 48-hr DARFs were used to validate the recommended DARFs. The goal of the validation procedure was to determine which DARF percentile should be recommended for design storm generation. Therefore, peak discharges simulated based on multiple DARF percentiles and locations were compared to previously published values estimated based on basic statistical methods (Bulletin 17 C) and model-based methods using other historical or basin-specific design storm standard (WHA studies). The same procedure was applied for multiple subbasins within the Trinity and Neches River Basins.

The testing included 25th, 50th, 75th, and 95th percentile DARFs. When tested the 25th percentile DARFs provided systematically lower peak discharge estimates as compared to other flood frequency methods, including Bulletin 17C. The 75th and 95th percentile DARFs provided peak discharges that were systematically higher than the other flood frequency methods. A comparative analysis was conducted to evaluate simulated peak discharge values based on varied DARF percentiles against those of the WHAs and Bulletin 17C for the Trinity River Basin and Neches River Basin. Figure 16 and Figure 17 show the comparisons of the simulated peak values based on the 50th and 75th percentile DARFs for the 10- and 100-yr against those of WHA for the Trinity River Basin and Neches River Basin, respectively. In both cases, the simulated peak discharge values align closely with the WHA values for the 10-yr and 100-yr storms. Based on the results of this task, the project team concluded that the 50th percentile DARFs should be used for model-based peak discharge frequency analysis across Texas. The final recommended DARF curves for multiple durations, return period groups, and zones are included in Appendix 5.

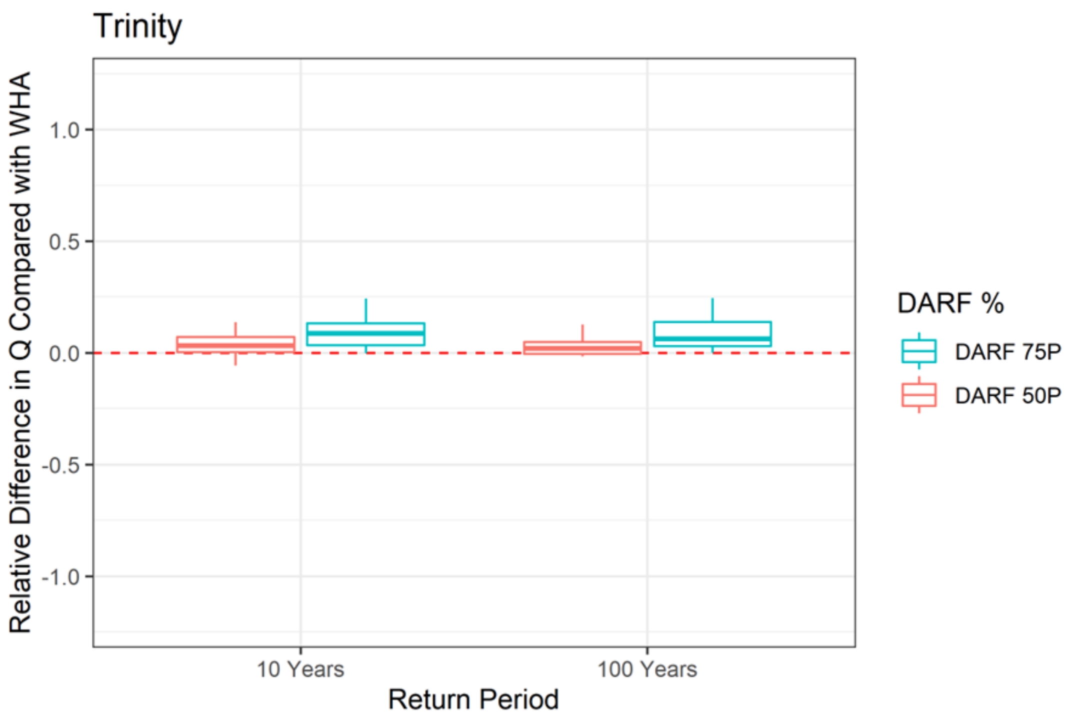

Figure 16: Relative difference for simulated peak discharge at all locations to the WHA for different frequencies (10-yr and 100-yr) in the Trinity River Basin

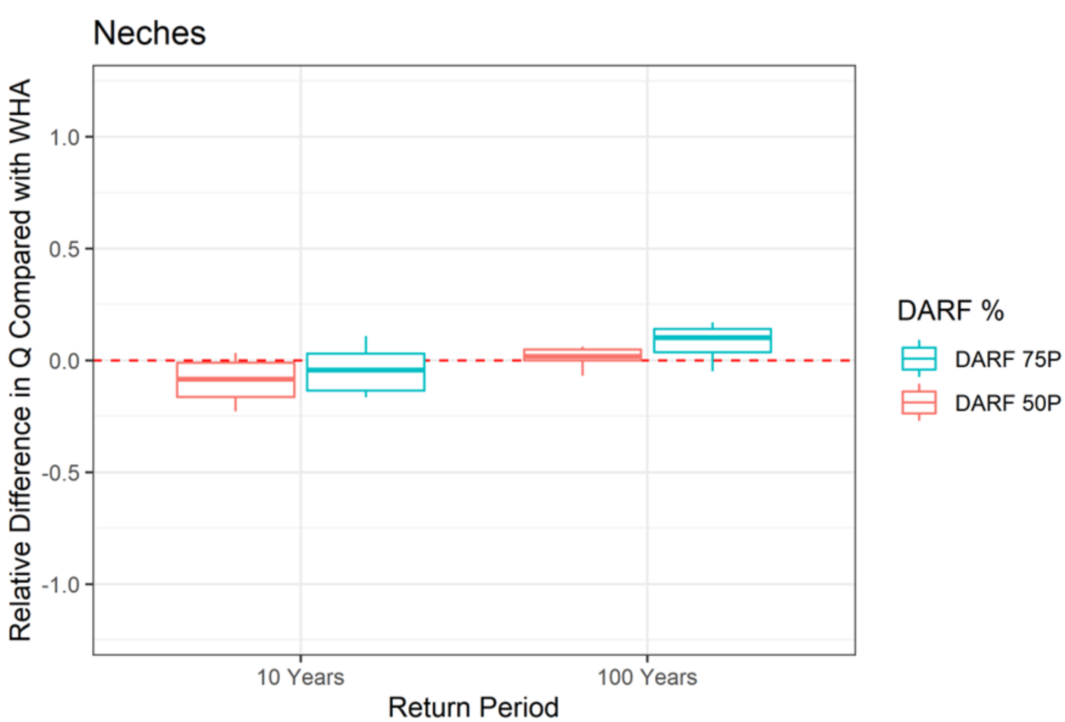

Figure 17: Relative difference for simulated peak discharge at all locations to the WHA for different frequencies (10-yr and 100-yr) in the Neches River Basin

2.5.2. Validation for the Northwest Zone: Additional Analysis Performed by USACE

The team analysis focused on basins that are in the Eastern Zone because those were the WHAs reports that were publicly available. The USACE applied the Colorado River basin models to apply a similar methodology to verify the DARF values at the Northwest Zone.

To ensure that the 3 ranges of DARFs return periods do not cause discontinuity in a frequency curve, the 50th percentile DARFs were further tested across multiple return periods (2-, 5-, 10-, 25-, 50-, 100-. 200-, and 500-yr). DARFs with a large range of durations (1-, 2-, 3-, 6-, 12-, and 24-hr durations) were tested in the analysis.

The USACE concluded that peak flows obtained based on the 50th percentile for multiple return period and duration DARFs aligned well with those of the Bulletin 17C analysis and the model-based peak discharge frequency analysis values within the WHAs. These results corroborate the results obtained by the team for the Trinity and the Neches basins.

2.6. DARF Database

Task 6 –DARF Database included the development of a user-friendly and interactive web tool to provide data for practitioners with different levels of expertise. The report showcases a demonstration of the workflow and environment of the Web-based DARF Tool. This advanced ArcGIS Online-based graphical user interface tool presents the TSS results and facilitates the retrieval and interpretation of DARFs in the corresponding Texas zones. Its interactive modules provide visualization of DARF curves and allow for downloading DARF values in a .csv format, with a feature to identify recommended DARFs for specific zones by clicking on desired coordinates or searching addresses. The dashboard is hosted at the ESRI Cloud Server and can be accessed at the link (https://bit.ly/DARFtool[2]).

Appendix 6 details the methodology behind the tool's development and the interaction of each module, underscoring its utility in enhancing flood design capabilities. Instructions on how to access and use the tool are provided in Section 5 - Example Problem and Design Storm Building Resources of this report. The tool supports decision-making for engineers, policymakers, and the public, aiming to improve flood risk management in Texas.

3. Design Storm Methodology and Procedures

3.1. Elliptical Design Storm

To account for a natural storm, an elliptical shaped storm pattern is recommended in this study, especially when considering the hydrologic response from large watersheds (> 400 sqmi). Several elliptical storm characteristics can influence peak discharge, including storm size, angle, maximum depth at center, and the DARFs. However, DARFs are highly variable and influential and are the focus of TSS.

[2] Texas Storm Study - DARF dataset (arcgis.com)
https://www.arcgis.com/apps/dashboards/7a800ce84f424689955593fa88c42fe5

Elliptical shaped storms have been used in a variety of hypothetical design applications, including the probable maximum precipitation (PMP) storms with the DARFs from Hydrometeorological Report No 52 (HMR 52) (Hansen et al, 1982). Currently, the depth-area analysis in HEC-HMS applies the appropriate DARFs to the given point rainfall depths based on the drainage area at a given evaluation point, which are derived from the published DARFs from the National Weather Service TP-40 (Herschfield, 1961).

The TSS provides a comprehensive DARF database tested with several hydrologic analyses for the Trinity, Neches, and Colorado River Basins. This section outlines a brief procedure of how to use the updated DARF database for generating an elliptical design storm for a watershed.

3.2. Updated DARFs

This study provides updated DARF data for multiple durations (1-, 2-, 3-, 6-, 12-, 24-, and 48-hr) and return frequencies (2-yr <Return Period <= 50-yr; 50-yr < Return Period < 200-yr; Return Period >= 200-yr) and three homogeneous DARF zones (East, Northwest, and West Zones) in Texas. Based on the results of Task 5, 50th percentile DARF curves are recommended for design. The 50th percentile DARF curves are provided in this report (Section 3.4.3.) in Figure format. However, to simplify the application of the data the final recommended curves are also provided by the Web-based DARF Tool described in Section 3.6.

3.3. Considerations for Design Storm Parameters

Storm Duration: The critical storm duration, which refers to the storm duration that results in the peak discharge for the duration of interest, varies with the size of the basin, the specific goals of the study, and regional climate patterns. While peak discharge is a near instantaneous value, a project might require the specification of the peak discharge over longer durations (e.g., reservoir design might require the quantification of maximum volumes over a 1, 2 or 3-day period). For being so broad, and including many different variables, the definition of the discharge and storm duration of interest are not specified in this standard and is the responsibility of the engineer in charge.

Storm Size: The current recommended storm size is 10,000 square miles. The size of 10,000 square miles. was selected since it represents close to the 50th percentile of storm sizes in the storm dataset (see Figure 4). Such a storm would completely cover small basins, while providing partial coverage to larger watersheds.

Total Rainfall Depths: Elliptical storms can be constructed for any return period available from NOAA Atlas 14 (2- to 1000-yr). Rainfall depths should be extracted from NOAA Atlas 14 or future advances.

Ellipse Ratio: A ratio of 3:1 or 2.5:1 is typically used for the major and major axes of an ellipse, but it may be adjusted to better match the shape of a particular basin. Statistics on elliptical shape for a 60-min storm is presented in Appendix 5.C.

Storm Temporal Pattern: The alternating block temporal pattern (the 50% HEC-HMS frequency storm distribution) is often applied due to its simplicity and maintaining the proper intensity throughout the storm period. However, the ideal temporal distribution depends on the project location, and should be determined by engineers performing the analysis. The example problem will provide more detail on how to compute a design storm temporal pattern based on the NOAA Atlas 14 rainfall depths.

Optimization of Storm Location and Rotation: The elliptical storm location (center) and rotation that result in the peak discharge for each location of interest needs to be determined. That procedure can be performed manually (visually optimize the volume of rainfall over the area of interest) or through an optimization algorithm. Placing an elliptical storm with the peak rainfall located over the watershed centroid is a good start.

4. Example Problem and Design Storm Building Resources

The TSS provides guidance for an advanced approach to hydrologic analyses by incorporating DARFs into the design storm process. This section demonstrates the TSS's comprehensive methodological framework by illustrating a case study of the West Fork of Trinity River at Boyd. It showcases how DARF values can be incorporated into the conventional design storm process, based on the information generated by the study. The example aims to guide users through six sections in integrating DARF values and NOAA Atlas 14 precipitation data to develop hyetographs to be used as input to a lumped hydrological model (e.g., HEC-HMS): (1) Site Selection and Initial Analysis, (2) Storm DARF Retrieval, (3) Precipitation Data Retrieval, (4) Construction of Elliptical Design Storms, (5) Hyetographs of Constructed Design Storms, and (6) Evaluation. The framework presented here would work with a gridded hydrology model but some of the development steps would have to be adjusted. For simplicity, this example only demonstrates a process of using a set of DARF values and NOAA Atlas 14 precipitation data for the 100-year and 48-hour storm for modeling of the study watershed using HEC-HMS (V4.12).

4.1. Step 1: Site Selection and Initial Analysis

This section presents an example of how to apply the DARF data generated by the TSS. The method is applied to the West Fork of Trinity River at Boyd. Figure 18 illustrates the selected site: the West Fork of Trinity River at Boyd, marked by the USGS stream gage number 08044500.

The West Fork of Trinity River at Boyd was chosen as a representative location to demonstrate practical applications of the toolkit and not for demonstrating its individual hydrologic significance to the watershed. This example aims to illustrate how practitioners can use the toolkit to enhance hydrometeorological analyses and flood risk assessments across various points within any watersheds of Texas. While this study produced many DARF values for watersheds in the three zones, as stated in the previous sections, this example only demonstrates a process of using the DARF values and NOAA Atlas 14 precipitation data for the Upper Trinity River Basin 100-year and 48-hour storm, which is located in the East Texas Zone. Users are encouraged to follow this procedure to apply corresponding DARF values to any other watersheds in Texas.

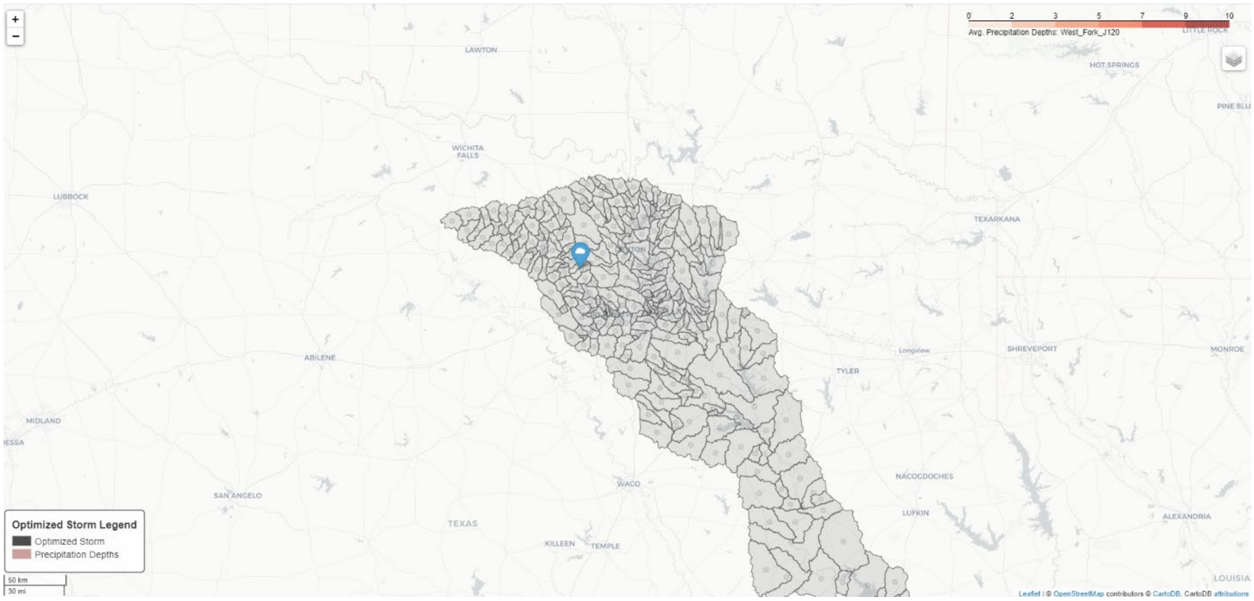

Figure 18: Site location and West Fork of Trinity River at Boyd (USGS 08044500)

4.2. Step 2: Storm DARF Retrieval

The Web-based DARF Tool is an ArcGIS-based platform to provide DARFs and elliptical storm templates for hydrological modeling across different watersheds in Texas (https://bit.ly/DARFtool[3]). This tool was developed as part of the TSS funded by the USACE. The dashboard of the tool consists of three modules: (**A**) Interactive Map (top), (**B**) Download Panel (right), and (**C**) Visualization Panel of DARF Curves (bottom). These modules enable users to select, visualize, and download DARF data and elliptical storm templates tailored to corresponding watersheds in Texas.

The process of developing design storms starts with identifying and selecting corresponding meteorological zones for any watersheds of interest within the mapping panel. Utilizing the dashboard, users can select and retrieve corresponding DARF values for desired watersheds, which can be visualized in the bottom panel. The tool allows users to download selected DARF values as .CSV files from the right panel. In this example, since the site of interest resides in the Upper Trinity River Basin as part of the East Texas Zone, users will download the DARF data for the East Texas Zone along with a storm template shapefile with a suitable ratio for the watershed. Figure 19 illustrate the steps of (**A**) navigating the dashboard and selecting the appropriate zone, (**B**) downloading the DARF for a 100-year return period with a 48-hour duration, and (**C**) selecting and downloading the storm template shapefile with the suitable ratio. Users may refer to Appendix 6 for more information on the Texas Web-based DARF Tool. The detailed instructions of retrieving DARF values are shown below.

[3] Texas Storm Study - DARF dataset (arcgis.com)
https://www.arcgis.com/apps/dashboards/7a800ce84f424689955593fa88c42fe5

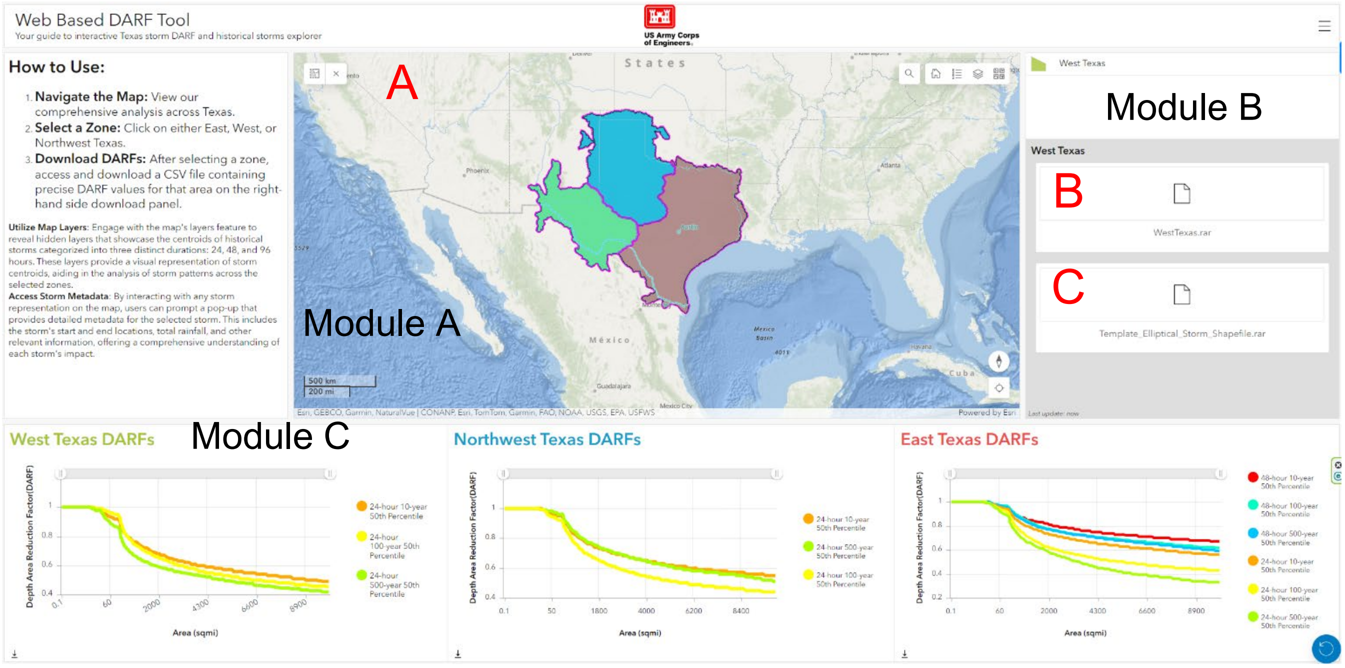

Figure 19: Texas Web-based DARF Tool Dashboard consisting of three panels of mapping (top), Dashboard guideline (left), and downloading DARFs (right). Users can navigate to (A) Select corresponding meteorological zones in the mapping panel. In this case, the East Texas Zone is selected on the mapping panel for further retrieval of the DARF values for the study area; (B) Download the DARFs as CSV files; (C) Download the shapefiles of elliptical storm templates

Download Instructions

A. **Access the Web-based DARF Tool and Select the East Texas Zone**:

- Navigate to the Web-based DARF Tool via the hyperlink of https://bit.ly/DARFtool[4]
- Either click directly on the **East Texas Zone** on the Interactive Map (Module A) or select it through the Zone Selection Panel (Module C).

B. **Download DARF .RAR File**:

- Download the **.RAR** file containing **.CSV** files with DARF values for elliptical storm templates.
- Extract the contents of the **.RAR** file.

C. **Select and Download the Upper Trinity Template**:

- The **.RAR** file contains two elliptical storm shapefiles:

[4] Texas Storm Study - DARF dataset (arcgis.com)
https://www.arcgis.com/apps/dashboards/7a800ce84f424689955593fa88c42fe5

- **3:1 Ratio Elliptical Storm Shapefile**
- **2.5:1 Ratio Elliptical Storm Shapefile**

- Choose the **3:1 ratio template** for the Upper Trinity River Basin because the West Fork of Trinity River at Boyd resides in the Upper Trinity River Basin.

4.3. Step 3: Precipitation Data Retrieval

Users will select and download precipitation information for any design storm return period and durations once desired DARF values are retrieved for the Web-based DARF Tool. This step shows users how to download high-resolution precipitation data (100-year and 48-hour) directly from the NOAA Atlas 14 Precipitation Frequency Data Server (PFDS). Figure 20 illustrates a process of retrieving the 100-year and 48-hour precipitation data in a GIS format from the NOAA Atlas 14 website. The retrieval process can be completed via the following steps:

A. **Pick the State of Texas for GIS data retrieval**
B. **Chose the type of precipitation as "Precipitation frequency estimates"**
C. **Select the annual maximum series**
D. **Select the return period of the storm**
E. **Select the duration of the storm**
F. **Download the data**

The downloaded data will contain high-resolution precipitation estimates in ASCII format, ready to be used in ArcGIS for further analysis.

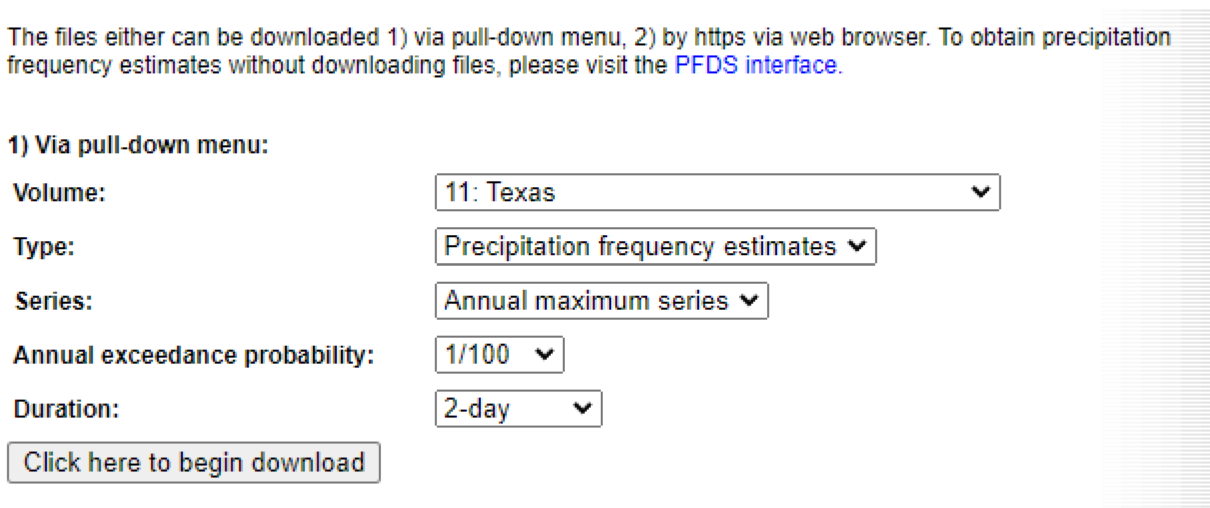

Figure 20: NOAA Atlas 14 interface for downloading precipitation data.

4.4. Step 4: Construction of Elliptical Design Storms

This step relies on the retrieved information from the prior three steps (site information, DARFs in raster, and NOAA Atlas 14 precipitation data in raster) to create an elliptical storm with the optimized centroid location and orientation that leads into maximum simulated peak discharge. For lumped hydrological model application, the constructed elliptical storm can be further translated into hyetographs (time-series rainfall intensity) by the estimation of mean areal precipitation (MAP) .

The centroids and orientations of elliptical storms were taken from the InFRM Watershed Hydrology Assessment for critical locations of the Trinity River Basin including the West Fork at Boyd. The optimization process is not described in this example. For more information, users may visit the InFRM website with published reports to find critical storm centers from all the completed WHAs. Figure 21 shows a process of constructing an elliptical design storm and generating MAPs to the contributing subbasins with four major steps (A, B, C, and D) as described below:

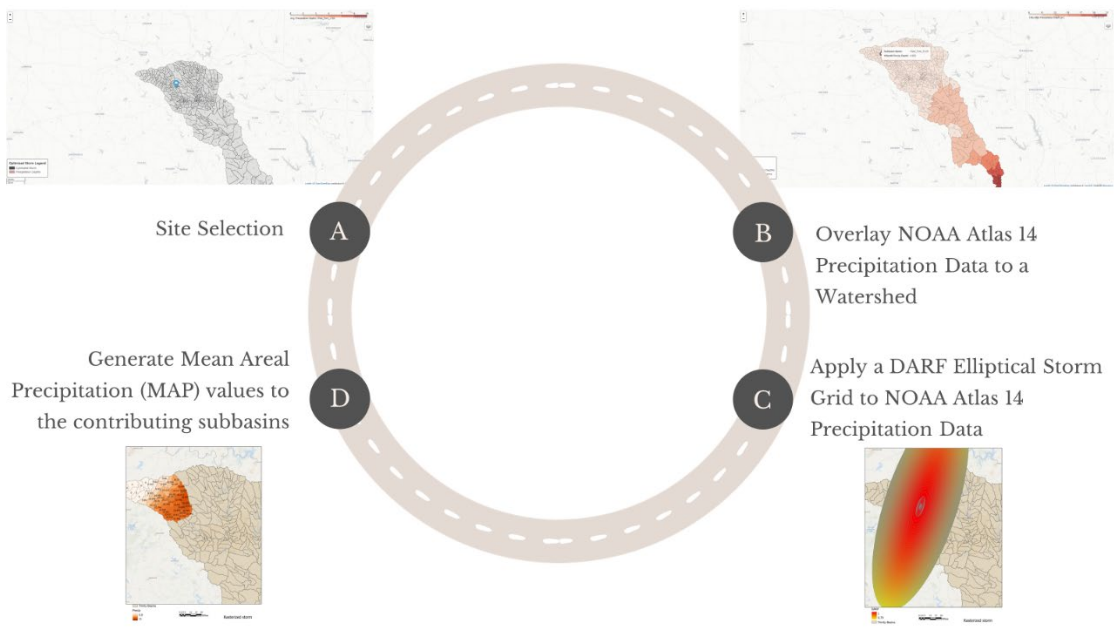

***Figure 21**: Flowchart of generating mean areal precipitation (MAP) data to the contributing subbasins of the West Fork of Trinity River at Boyd (USGS 08044500).*

A. **Prepare a Watershed Map and Identify the Site of Interest:** a detailed map of the watershed will be prepared to ensure that each subbasin is clearly delineated and the site of interest resides within the watershed;
B. **Move the ellipse to the location of interest:** Users will adjust the DARF values for the specific region, duration, and return period applicable to the project using the DARF values retrieved from the Web-based DARF Tool as a .CSV file, then paste these values into the DARF column of the elliptical storm template shapefile. Subsequently, the elliptical storms can be moved and rotated based on recommended locations and orientations for the sites of interest.
C. **Apply DARF Values:** The elliptical storm shapefile needs to be transformed into a raster

using the "Polygon to Raster" tool in ArcGIS Pro. The storm raster is further multiplied by the NOAA Atlas 14 precipitation raster using the "Raster Calculator" tool in ArcGIS Pro, which integrates the storm-specific reduction factors with the NOAA Atlas 14 precipitation data to be allocated to the watershed.

D. **Allocate Precipitation Values to Subbasins:** Users may use "*Zonal Statistics as Table*" to calculate the MAP values as a shapefile for the contributing subbasins. Figure 22 illustrates the generated MAP depths in a shapefile for the contributing subbasins as the final product of **Step 4**

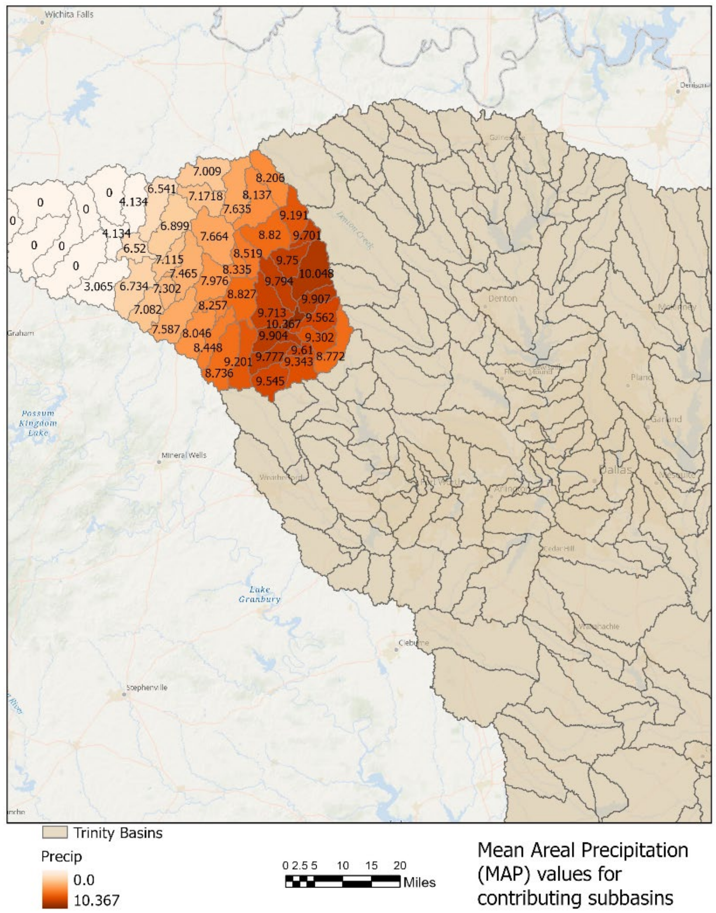

Figure 22: Illustration of the mean areal precipitation (MAP) depth values for the contributing subbasins of the West Fork of Trinity River at Boyd (USGS 08044500)

4.5. Step 5: Hyetographs of Constructed Storms

Once rainfall totals of the 100-year and 48 hours storm are obtained for the contributing subbasins, users may utilize the alternating block method to build hyetographs for individual subbasins. The alternating block method has been widely used to generate time-series rainfall distributions based on rainfall totals, frequencies, and durations. This method is commonly used to prepare time-series rainfall input for hydrologic simulation, so a simple description of the procedures shows a brief process for one of the contributing subbasins (WEST_FORK_S210) only.

1. **Obtain Frequency Precipitation Estimates for the 100-Year Storm with Durations Up to 48 Hours**:
   - User may download the 100-year precipitation estimates with durations (5-min, 10-min, 15-min, 30-min, 60-min, 2-hr, 3-hr, 6-hr, 12-hr, 24-hr, and 2-day) for the centroid of one of the contributing subbasins (WEST_FORK_S210) from the NOAA Atlas 14 website. The downloaded data presents a relationship of the cumulative precipitation depths with a duration of up to 48 hours for the 100-year storm.
2. **Distribute Precipitation Totals into Alternating Blocks**:
   - Users may apply the interpolation techniques to determine all precipitation depths on an hourly basis for up to 48 hours, then yield successive differences from the cumulative depths, resulting in a set of incremental precipitation values. The yielded incremental precipitation values (48 blocks) need to be arranged in descending order.
   - Users then need to rearrange the incremental precipitation values (48 blocks) from the original descending order from the previous step into a new order, as shown in Table 3.

Table 3: Original and new orders of the temporal distributions for the incremental precipitation values (48 blocks) for the contributing subbasin (WEST_FORK_S210).

Original Order of Hourly Time Stamps	New Order of Hourly Stamps	Original Order of Hourly Time Stamps	New Order of Hourly Stamps	Original Order of Hourly Time Stamps	New Order of Hourly Stamps	Original Order of Hourly Time Stamps	New Order of Hourly Stamps
1	25	13	31	25	37	37	43
2	24	14	18	26	12	38	6
3	26	15	32	27	38	39	44
4	23	16	17	28	11	40	5
5	27	17	33	29	39	41	45
6	22	18	16	30	10	42	4
7	28	19	34	31	40	43	46
8	21	20	15	32	9	44	3
9	29	21	35	33	41	45	47
10	20	22	14	34	8	46	2
11	30	23	36	35	42	47	48
12	19	24	13	36	7	48	1

   - The re-arranged incremental precipitation values in the new order become a time-series rainfall distribution (hyetograph) with a duration of 48 hours.

3. **Enter Data into HEC-HMS or DSS**:

    - The processed time-series precipitation data can be directly entered into HEC-HMS or stored as a DSS file for future use.

By following these steps, users can generate time-series precipitation data for other contributing subbasins to run hydrologic simulations in HEC-HMS. Users can also use the data from **Step 5** to generate the gridded precipitation data for distributed hydrologic models based on specific needs.

4.6. Step 6: Evaluation

This section intends to illustrate the enhanced precision and realism achieved through the application of the methodologies outlined in **Steps 1** through **5** of this example of the TSS by showing tangible benefits of employing DARFs in hydrologic modeling. By comparing two storm grid scenarios—one modeled with uniformly distributed rainfall with no reduction and the other with DARFs applied—this section highlights the importance of incorporating DARFs to design storms for further hydrologic modeling.

Figure 23**a** showcases a storm (100-year 48-hour) grid with a uniform rainfall distribution in an elliptical storm shape for the site of interest. It represents a scenario when the storm's precipitation is spread evenly across the contributing subbasins with no reduction, serving as a baseline for comparison against the more sophisticated DARF-incorporated storm grid. The MAP total depth of the 100-year 48-hour uniform design storm for one of the contributing subbasins (WEST_FORK_S210) is 10.45 inches.

Figure 23**b** illustrates the storm (100-year 48-hour) grid with corresponding DARFs applied to an elliptical storm shape. The resulted elliptical storm grid shows reduced rainfall depths with more spatial variability internally. For the contributing subbasin (WEST_FORK_S210) as an example, the corresponding MAP total of 8.78 inches of the 100-year 48-hour design storm, indicating the reduced total rainfall depths due to applied DARF values.

The side-by-side comparison of the spatial distribution and the intensities from both scenarios underscores the importance of DARFs in capturing the nuanced spatial variability of rainfall across a watershed.

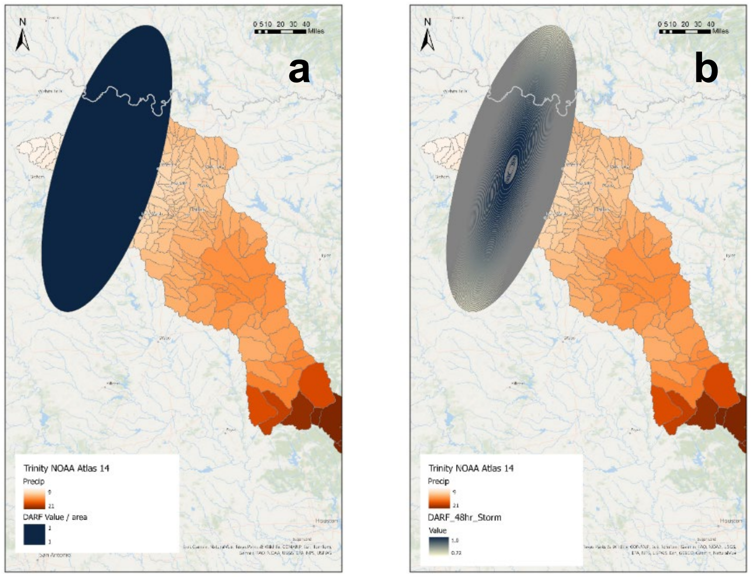

Figure 23: a) Uniformly distributed storm grid with no DARF applied; b) Spatially distributed storm grid with DARF applied.

5. Study Limitations and Unexpected Findings

The TSS focused on providing guidance and standards for the development of elliptical design storms for use in model-based peak discharge frequency analysis over Texas for large basins. The team evaluated many storms to extract general properties of storms in Texas. The State was divided into three zones with similar storm characteristics: East, Northwest, and West Texas. The methodology proposed in this study was validated based on statistical and model-based results published in the literature for the Eastern and Northwestern Zones. No approved hydrological model study was available to validate DARF for the West Zone. The recommended DARF values are provided in a user-friendly web interface.

Other important aspects for model-based peak discharge frequency analysis were not in the scope of the TSS, including recommended initial conditions, infiltration parameters, storms' temporal distributions, and sequences of storms.

One important unexpected outcome from the TSS is the finding that continuous (uninterrupted in time) storms in Texas rarely span a 2-day duration. For that reason, the storm sample size for storms longer than 2 days was small compared to other durations, and for some of the zones not considered large enough to draw definitive conclusions on DARF shape. This is not to say that longer duration non-continuous storm events do not have a strong impact on peak discharges. The effect of multiple storm sequences on peak discharge is expected to change with drainage area, since the basin critical storm duration is also expected to change with drainage area.

This study focused on design storms with an elliptical shape whose center remains fixed over the area of interest during the development of the storm. Storm intensity changes with time. This methodology was applied in earlier WHA studies published by InFRM and was the focus of the

TSS. It represents a large advance in comparison with the traditional approaches of applying a uniform rainfall distribution over the basin.

Other more complex methodologies to develop design storms have been proposed and applied in the literature. The evaluation and development of standards for those methodologies were outside of the scope of this study. A list of methods that can be applied to generate storm inputs for model-based peak discharge frequency analysis, ordered by level of increasing complexity is listed in Table 3.

Table 4: Design storm methodologies. Synthetic storm design methods are highlighted in blue, while methods that rely on real storm transpositions are highlighted in green.

Design Storm Type	Characteristics
Uniform Storm	Uniform in space. Varies in time.
Elliptical Storm	Spatially varying in space, but the center of the ellipse is kept in the same location throughout the storm. Uses one DARF that corresponds to the maximum duration of the storm. Varies in time. This type of event was the focus of this study. Not recommended for large basins.
Elliptical Storms with DARF varying by temporal resolution (top-down)	Like the Elliptical Storm method, but the DARF varies with the temporal resolution of the storm. Tends to be less conservative than the Elliptical Storm since it adopts DARF with higher temporal resolution which tends to decrease faster than DARFs with lower temporal resolution. This method is also called top-down since storms are built starting at the longest storm duration (e.g., 2-day) and systematically moving through other higher temporal resolutions. This was not the focus of this study, but lots of information generated during this study may apply.
Dynamic Elliptical Storms (bottom-up)	Focus on reproducing storm characteristics at small temporal scale (e.g., 1-hr). Previous studies have shown that the storm characteristics at long-duration are preserved when using this method. The elliptical high-resolution storm dynamically moves over the area of interest with characteristics that resemble real storms (e.g., direction, speed, angle). This was not the focus of this study, but a lot of information generated during this study is relevant to dynamic elliptical storms.
Storm Transposition	This method uses real extreme storms that can be transposed to the area of interest. Transposition limits should be clearly defined based on weather patterns, and the topography of the area of interest. Storm intensities are then shifted up or down to match the areal precipitation frequency for the return period of interest. DARF is still required since point precipitation frequency estimates are still used.
Stochastic Storm Transposition	Uses a large database of storms within a transposition zone to estimate areal precipitation frequency over a basin of interest. By replacing time with space, a large catalog of plausible storms over the basin is created, which theoretically allows for smaller uncertainties in frequency analysis. Once areal precipitation estimates for multiple return periods are available, design storms can be built using multiple spatial and temporal distributions obtained from the transposed storms. This method does not directly require the use of DARFs. However, DARFs can be used to validate the transposed storm sample to ensure correct representation of storm volumes.

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