Updating the Texas Rainfall Coefficients and Enhancing the EBDLKUP Tool: Technical Report

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Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE
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16. Abstract

Currently, the Texas Department of Transportation (TxDOT) uses EBDLKUP-2015-V2.xls to estimate location-specific storm intensities for hydraulic design. This tool is based on storm frequency and duration data analyzed and summarized between 1998 and 2004. In 2019, the National Oceanic and Atmospheric Administration Atlas 14 project released the results of new data on the depth, duration, and frequency of storms within Texas. This study describes methods and analyses to incorporate the new Atlas 14 data into TxDOT's hydraulic design process. The outcome of the study is a new hydraulic design tool provisionally named EBDLKUP-2019. This tool improves the accuracy of statewide hydraulic design in two ways. First, it incorporates the latest information on the statewide spatial pattern of storms into the hydraulic design process. An analysis detailing how this spatial pattern has changed since the development of the previous tool is included in this report. Second, the tool improves the spatial accuracy of rainfall intensity predictions to subcounty rainfall zones. An analysis detailing the derivation of these subcounty rainfall zones is also provided in the report.

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The researcher in charge of this project was Andrew Birt.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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LIST OF SYMBOLS AND ABBREVIATIONS

AEP	Annual exceedance probability
AMS	Annual maximum series
ARI	Annual recurrence interval
CRIS	Crash Records Information System
DDF	Depth-duration-frequency
FHWA	Federal Highway Administration
GEV	Generalized extreme value
GIS	Geographic information system
GLO	Generalized logistic
IDF	Intensity-duration-frequency
KML	Keyhole Markup Language
NOAA	National Oceanic and Atmospheric Administration
PDS	Partial duration series
PRESS	Predicted residual error sum of squares
SSQ	Sum of squares
t_c	Time of concentration
TTI	Texas A&M Transportation Institute
TxDOT	Texas Department of Transportation
URL	Uniform Resource Locator
USGS	U.S. Geological Survey

CHAPTER 1. INTRODUCTION

This report describes research conducted under Texas Department of Transportation (TxDOT) Research Project 0-6980, Update Rainfall Coefficients with 2018 National Oceanic and Atmospheric Administration (NOAA) Atlas 14 Rainfall Data. Project 0-6980 deals with incorporating newly released NOAA Atlas 14 rainfall depth-duration-frequency (DDF) data into the TxDOT hydraulic design process. Specifically, the project deals with incorporating Atlas 14 data into TxDOT's current and established method of predicting rainfall intensities for designing hydraulic structures for small watersheds.

HYDRAULIC DESIGN USING THE RATIONAL METHOD

The Atlas 14 data provide high-resolution, spatially explicit estimates of rainfall DDF across Texas. TxDOT, in collaboration with other hydraulic engineers and scientists, has developed standard methods by which this information can be used to design hydraulic structures to mitigate flooding. In Texas, the rational method is the standard model used to estimate the peak runoff from small watersheds (typically less than 200 acres). The rational method uses the following formula:

$$Q = CIA \qquad \text{Equation 1}$$

Where:

- Q is the maximum rate of runoff.
- C is a runoff coefficient.
- A is the size of the drainage area.
- I is rainfall intensity.

Hydraulic structures are designed for a specified design storm characterized by the duration of rainfall and the probability of occurrence. For the rational method, a design storm is based on a worst case storm duration for a specified storm frequency (e.g., a 1 in 50-year storm). The worst case storm duration depends on the time of concentration (t_c) of the watershed, which is the minimum time taken for runoff to reach peak flow. The rainfall intensity (I) of the design storm is then used as an input to the rational method, which translates these storm characteristics into estimates of surface runoff (or other hydraulic endpoints) that are the focus of the hydraulic design.

At the end of this design process, an engineer can express the frequency (or probability) with which a hydraulic design is expected to flood, given the rainfall and watershed characteristics at a specific location. The risk-based approach to design ensures that hydraulic structures balance the economic cost of implementing hydraulic designs against known consequences of flooding—for example, damage to transportation infrastructure, impacts on traveler safety, and impacts on mobility. By specifying standardized hydraulic design methods, procedures, and data, TxDOT (and other stakeholders) can reduce the cost of designing effective hydraulic infrastructure and maintain consistent, equitable, and verifiable design standards across the state.

TEXAS RAINFALL COEFFICIENTS

The rational method requires accurate, location-specific information on rainfall and requires engineers to characterize a design storm at a specified location by:

- The frequency with which it occurs in the climate record.
- A specified storm duration based on t_c.

In Texas, the following intensity-duration-frequency (IDF) function is used:

$$I_{ARI,location} = \frac{b}{(t_c+d)^e} \quad \text{Equation 2}$$

Where:

- $I_{ARI,\ location}$ is the storm or precipitation intensity for a specified annual recurrence interval (ARI) and location.
- t_c is the time of concentration or critical duration of the storm.
- *e*, *b*, and *d* are fitted parameters.

The parameters *e*, *b*, and *d* in Equation 2 are derived by fitting the equation to data on the frequency and intensity of storm events at a specific location (e.g., those provided by Atlas 14). Typically, DDF studies provide storm frequency data for a range of fixed, distinct (non-continuous) durations and frequencies. For example, the Atlas 14 project provides rainfall depth information for storms of 2, 5, 10, 15, 30, and 60 minutes; 1, 2, 3, 6, 12, and 24 hours; and 2, 3, 4, 7, 10, 20, 30, 45, and 60 days. The Atlas 14 project also provides depth data for storm frequencies of 1, 2, 5, 10, 25, 50, 100, 250, 500, and 1000 years. Equation 2 enables engineers to estimate rainfall intensity for a design storm specified by frequency and by an exact (continuous) storm duration.

PRACTICAL APPLICATION— EBDLKUP TOOL

Standard methods (including the rational method) for designing hydraulic structures for TxDOT projects are documented through the TxDOT *Hydraulic Design Manual*. TxDOT also provides engineers with a spreadsheet tool to estimate rainfall intensity using Equation 2. The tool (called EBDLKUP-2015v2.1) contains *ebd* coefficients that define the IDF characteristics of storms typically found in each of the 254 counties in Texas. To use the tool, an engineer enters the county within which a project is located and a t_c value representative of the project watershed. The tool uses a built-in database of *ebd* coefficients (defined for each county) and Equation 2 to estimate rainfall intensity for annual exceedance probability (AEP) between 50 percent and 1 percent.

TRANSLATING DDF DATA TO IDF COEFFICIENTS

The *ebd* parameters currently used by TxDOT in its design processes were developed by Cleveland et al. (2015). These *ebd* coefficients were fit to DDF data provided through two TxDOT-sponsored studies: Depth Duration Frequency of Precipitation for Texas by Asquith (1998), and Atlas of Depth-Duration Frequency of Precipitation Annual Maxima for Texas by Asquith and Roussel (2004). These studies estimated spatial DDF data for storm durations of 10, 15, and 30 minutes; 1, 2, 3, 6, 12, and 24 hours; and 1, 2, 3, 5, and 7 days; and frequencies of 2, 5, 10, 25, 50, 100, 250, and 500 years.

The DDF data from the Atlas 14 study supersede the data generated by Asquith (1998) and Asquith and Roussel (2004). The Atlas 14 project benefits from improved precipitation data brought about by increases in the number of weather stations, improvements in the temporal resolution of precipitation data, and the simple fact that the climate record is now longer than in 1998. The Atlas 14 project also incorporates a spatial interpolation method that delivers DDF data at a resolution of 30 arcseconds (approximately 0.008 decimal degrees or 0.5 miles).

GOALS OF THE PROJECT

The goals of this project were as follows:

- Convert the new DDF data provided by Atlas 14 into spatially explicit *ebd* coefficients that can be used to predict location-specific rainfall intensity using Equation 2.
- Update TxDOT design tools (e.g., EBDLKUP-2015v2.1) so that the new *ebd* coefficients can be used efficiently and reliably within TxDOT's hydraulic design process.

CHAPTER 2. STATE-OF-THE-PRACTICE REVIEW

Storm drainage is an integral part of the design of highway and transportation networks (Federal Highway Administration [FHWA], 2009). In a transportation context, the most common design goal is to prevent flooding in and around roads or other transportation structures. Surface water on roadways represents a significant safety risk, while repeated flooding damages transportation infrastructure (Pedrozo-Acuña et al., 2017). Transportation engineers may also be required to design hydraulic structures in line with other environmental regulations, for example to maintain existing hydrological function, mitigate waterborne pollutants, or provide safe passage or maintain habitat for wildlife.

Conceptually, storm water engineering considers the frequency, duration, and intensity of precipitation falling within a watershed, and the hydraulic processes that dictate how water moves within the watershed. A watershed is any area of land where precipitation collects and drains into a common outlet or, in the case of a closed system, to a common sink. Hydraulic design involves modeling the hydrological processes operating within a watershed and implementing structures that influence these hydraulic processes to achieve a stated goal (e.g., to prevent flooding).

HYDRAULIC DESIGN PROCESS

Flooding of natural and human-designed watersheds is inherently unpredictable because the main driver of flooding (precipitation) is also random. Storms have several dimensions important for influencing flood conditions including spatial extent, storm duration, and precipitation depth (or intensity). Each dimension has its own stochastic component that makes short-term predictions difficult or impossible. Because extreme rainfall events are difficult to predict, risk-based methods and processes are used to design many hydraulic structures.

The design process requires a designer to first determine the required level of protection of a hydraulic structure or structures. This level of protection is expressed as the frequency or probability of a specified event occurring. The AEP or ARI is used to express these probabilities or frequencies. The AEP defines the tolerance for failure of the hydraulic structure (i.e., flooding). For example, an AEP of 1 percent means that the structure(s) is (are) designed to flood with storms that have a 1 percent chance of occurrence in any given year, which happens in average one time out of 100 years over a long period of time. Specifically, the AEP implies that flood events during each year are random and independent; a 1 percent AEP can be interpreted as either one flood event occurring on average once every 100 years, or a 1/100 (1 percent) probability of a flood occurring in any single year. Another way of defining the level of protection is by specifying an ARI or return period. An ARI is the average time between exceedances of a given rainfall or flood event.

In addition to modeling the chosen AEP, engineers typically validate structures for a check flood (1 percent AEP). The check flood standard is to ensure the safety of the drainage structure in the event of capacity exceedance. In such cases, engineers are required to examine where flooding will occur and ensure private properties or other sensitive structures are not impacted. Another purpose of the check flood is to ensure flows beyond the design capacity will not result in damage to existing hydraulic structures. Table 1 summarizes the recommended design standards for various drainage facilities associated with transportation infrastructure in Texas.

Table 1. Drainage Design Standards Associated with Roads in Texas.

Functional Classification and Structure Type	Design AEP (Design ARI)				
	50% (2 yr)	20% (5 yr)	10% (10 yr)	4% (25 yr)	2% (50 yr)
Freeways (main lanes):					
Culverts					X
Bridges					X
Principal arterials:					
Culverts			X	[X]	X
Small bridges+			X	[X]	X
Major river crossings+					[X]
Minor arterials and collectors (including frontage roads):					
Culverts		X	[X]	X	
Small bridges+			X	[X]	X
Major river crossings+				X	[X]
Local roads and streets:					
Culverts	X	X	X		
Small bridges+	X	X	X		
Off-system projects:					
Culverts	FHWA policy is "same or slightly better" than existing.				
Small bridges+					
Storm drain systems on interstates and controlled-access highways (main lanes):					
Inlets, drain pipe, and roadside ditches			X		
Inlets for depressed roadways					X
Storm drain systems on other highways and frontage roads:					
Inlets, drain pipe, and roadside ditches	X	[X]	X		
Inlets for depressed roadways				[X]	X

Note: For most types of structures, a range of design frequencies are marked with an X. The recommended frequency is marked by square brackets.
Source: TxDOT (2016)

TRANSLATING STORM EVENTS TO SURFACE FLOW

Conceptually, rainfall falling within a watershed is subject to hydrological processes that influence the spatial and temporal flow of surface water to a watershed outlet (Figure 1). These processes include interception and storage by vegetation or other structures, infiltration into subsurface water, evaporation and transpiration, surface runoff, and channel flow. In turn, hydrological processes are determined by physical characteristics of the watershed including its size, topography, soil type, vegetation, and potential for water storage. Some of these physical factors do not change through time, while other factors, such as vegetation cover and soil saturation, may be influenced by season or previous storm events. Other factors may change over longer time frames or by human activities (e.g., land use and land cover).

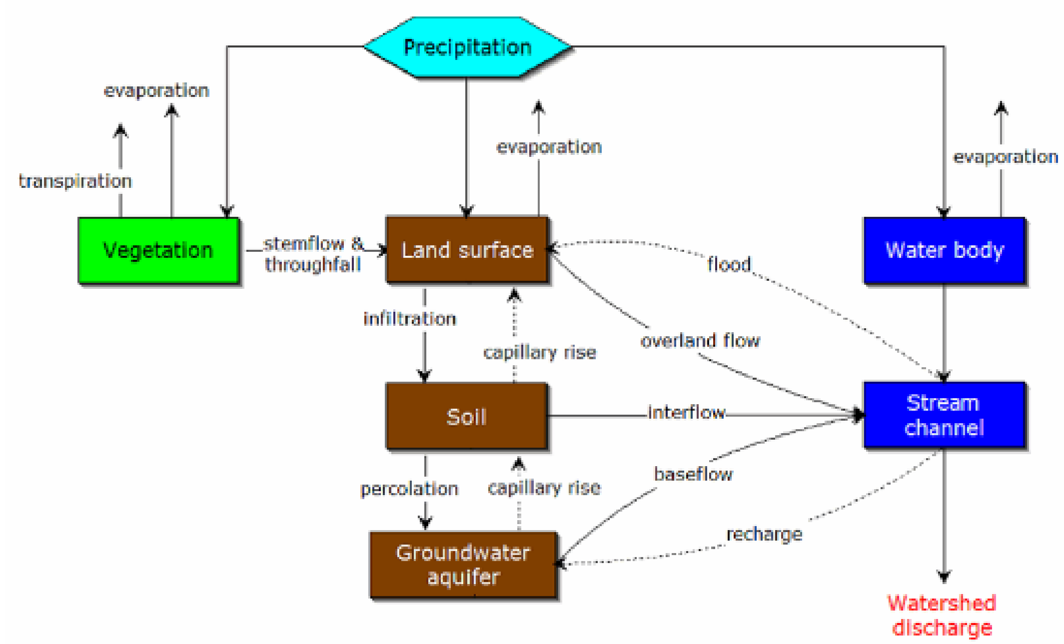


Figure 1. Hydrological Processes in a Watershed. Source: TxDOT (2016)

Hydraulic engineers have developed several methods to simplify and model hydrological processes within watersheds and translate discrete storm events into quantities such as peak flow. TxDOT recommends the following methods:

- Statistical analysis of stream gauge data. This method uses flow data from stream gauges to parameterize a probability model of peak annual discharge of the gauged channel. Therefore, this method does not explicitly model storm events or watershed processes that affect stream flow. Instead, the method uses stream flow data to determine peak flow or discharge of a stream.
- Omega EM regression equations. This method uses mean annual precipitation (for a given recurrence interval) to estimate peak discharge of a river or stream (for a specified frequency). This method uses simple equations that have been developed and verified through previous TxDOT research that relate watershed area, mean annual precipitation, and main channel slope to peak discharge. The method is applicable to natural basins greater than 1 square mile and preferably greater than 10 square miles.
- Hydrograph method. This method uses detailed mathematical models of hydrologic processes to transform individual storm events (specified for a recurrence interval) into runoff and peak flow. The hydrograph method differs from the rational method in that it

uses temporal descriptions of storm events (hyetographs) to estimate or predict temporal flow and volume (hydrographs). The temporal approach enables the method to represent hydrological processes such as infiltration or storage.

- Rational method. This simple method estimates peak runoff for a selected storm frequency. It is appropriate for urban and rural watersheds less than 200 acres (80 hectares) in which natural or man-made storage is minor, and is best suited to the design of urban storm drain systems, small side ditches and median ditches, and driveway pipes (TxDOT, 2016). The method translates a single independent storm event, defined by duration, intensity, and recurrence, into peak flow for the same AEP.

RATIONAL METHOD

The focus of this study is the development of IDF coefficients useful for hydraulic design using the rational method. The rational method of predicting AEP flows requires information on the intensity, duration, and frequency of storm events at a particular watershed.

The rational method assumes that peak flow is proportional to average rainfall intensity of a storm, watershed area, and runoff coefficient, which represents the proportion of precipitation that contributes to surface flow.

$$Q = \frac{CIA}{Z} \quad \text{Equation 3}$$

Where:

- Q is the maximum rate of runoff (cfs or m^3/sec).
- C is the runoff coefficient.
- I is the average rainfall intensity (in./hr or mm/hr).
- A is the drainage area (ac or ha).
- Z is the conversion factor: 1 for English[1] and 360 for metric.

The rational method simplifies hydraulic design by assuming that peak surface or channel flow is proportional to the intensity of the rainfall falling in a watershed. The runoff coefficient in Equation 3 represents losses into soil or depressions, which tend to reduce peak flow. TxDOT

[1] The actual conversion factor from acre-in/hour to cubic feet per second is 1.008, which is often simply rounded to 1 for convenience.

provides guidance, based on research, for estimating coefficients under various watershed conditions.

The watershed area term is based on the concept that larger watersheds tend to collect and concentrate more rainfall than smaller watersheds. The rational method assumes that a steady-state peak flow condition only occurs if the duration of a storm event is long enough for precipitation to reach an outflow from all areas of the watershed. Time of concentration (t_c) is the time required for an entire watershed to contribute to runoff at the point of interest—in other words, the time for runoff to flow from the most hydraulically remote point of the drainage area to the point under investigation. The method also assumes that the rainfall intensity is constant over the t_c. TxDOT provides guidance on how to approximate t_c for various design situations.

To use the rational method in design, an engineer undertakes the following steps:

1. Define an appropriate AEP for the planned hydraulic structure (e.g., 1 percent or an exceedance probability of 1 in 100 years).
2. Define and document pertinent features of the watershed (area and runoff coefficients).
3. Calculate the appropriate t_c value that will ensure that a storm event will be long enough for steady-state runoff to occur.
4. Determine a design storm intensity relative to the AEP, t_c, and geographic location of the watershed.
5. Use the information from steps 1 through 4 and Equation 3 to predict steady-state maximum flow conditions expected to occur for the defined AEP storm event (e.g., the calculated flow [cubic inches/hour] will be exceeded at a probability of 1 percent or 1 year out of 100).

ESTIMATING STORM INTENSITY BY FREQUENCY AND DURATION

Data describing the intensity, duration, and frequency of rainfall play a central role in predicting design flow and volume for hydraulic structures. For this reason, TxDOT provides several tools to obtain depth-duration-intensity data for a specified geographic location, frequency (AEP or ARI), and t_c. Figure 2 shows a screenshot of EBDLKUP-2015v2.1, a Microsoft® Excel™–based spreadsheet developed by TxDOT for predicting rainfall intensity for a specified Texas county.

Rainfall Intensity-Duration-Frequency Coefficients for Texas

Based on United States Geological Survey (USGS) Scientific Investigations Report 2004–5041
"Atlas of Depth-Duration Frequency of Precipitation Annual Maxima for Texas"

1. Select English or SI Units
English

2. Select or Enter a County
Brazos

3. Enter a Time of Conc.
Select Units
50 min

Coefficient	50% (2-year)	20% (5-year)	10% (10-year)	4% (25-year)	2% (50-year)	1% (100-year)
e	0.8147	0.8012	0.8028	0.8028	0.8067	0.798
b (in.)	56.19	70.86	85.71	106.03	128.46	143.06
d (min)	10.46	10.80	11.21	11.90	12.92	12.83
Intensity (in./hr)	1.99	2.64	3.15	3.86	4.55	5.26

(Spreadsheet Release Date: August 31, 2015; data table reshuffle by Asquith July 14, 2016)

Figure 2. TxDOT's Microsoft Excel–Based EBDLKUP-2015v2.1 Tool.

The descriptions of the rational methods illustrate the reasoning behind the design of the EBDLKUP-2015v2.1 tool. The tool is designed around the user specifying the t_c and the county of interest (these factors are derived from the watershed in question and are effectively independent variables). Using this information, the spreadsheet provides rainfall intensity for storm frequencies between 2 and 100 years (AEP of 50 to 1 percent). In the example illustrated in Figure 2, the tool estimates that a storm with a duration of 50 minutes in Brazos County, Texas, will have an intensity that exceeds 1.99 inches per hour once every 2 years (or a 50 percent chance in any year), or 5.26 inches per hour once every 100 years (or a 1 percent chance in any year). These rainfall intensities can be used, via the rational or hydrograph methods, to determine peak flow and to select structures capable of accommodating these peak flows.

CHAPTER 3. REVIEW OF DEPTH-DURATION-FREQUENCY AND INTENSITY-DURATION-FREQUENCY STUDIES

INTRODUCTION

This section describes cross-agency studies on DDF and IDF data, maps, and products for Texas. The production of DDF maps and data involves analyzing weather station data to produce an annual maximum series (AMS) of a specified duration. An AMS is the maximum storm depth, for a specified storm duration, recorded at a particular station each year. The AMS is used to parameterize probability distributions specific to a storm duration. In turn, these probability distributions can be used to derive storm depths (for a given storm duration) for any annual storm frequency.

The rational method of hydraulic design requires estimates or predictions of storm intensity for a ***specified*** storm duration (t_c) and for a specified return frequency (ARI or AEP). To facilitate design, TxDOT has developed models and tools to transform probabilities of storm depth (derived for a fixed number of storm durations) into probabilities of storm intensity for any specified storm duration.

Since 1970, TxDOT has sponsored research to develop data and tools that make it easier for hydraulic designers to obtain location-specific storm intensity data specified by storm frequency and storm duration (Tay et al., 2015). There have been two main foci of research:

1. Analysis of weather station data by storm duration to develop DDF maps and data products, referred to here as *DDF studies*.
2. Use of the products of step 1 to derive IDF models practically useful for hydraulic design, referred to here as *IDF studies*.

ATLAS 14 DEPTH-DURATION-FREQUENCY DATA

In 2002, the National Weather Service began the development of the NOAA Atlas 14. Atlas 14 contains precipitation frequency estimates DDF data with associated confidence limits. Atlas 14 provides a consistent methodology for calculating DDF data across the United States. The Atlas 14 project is divided into 11 regions (called volumes), chosen by area, and similarities of weather patterns (Table 2). The Atlas 14 website documents data collection and analyses methods for each volume, and includes a precipitation frequency data server developed to deliver DDF data to end users.

Table 2. NOAA Atlas 14 Volumes, Regions Covered, and Expected Release Dates.

Vol.	Title	Year
1	Precipitation-Frequency Atlas of the United States, Semiarid Southwest (Arizona, Southeast California, Nevada, New Mexico, Utah)	2004 (2011)
2	Precipitation-Frequency Atlas of the United States, Ohio River Basin and Surrounding States (Delaware, District of Columbia, Illinois, Indiana, Kentucky, Maryland, New Jersey, North Carolina, Ohio, Pennsylvania, South Carolina, Tennessee, Virginia, West Virginia)	2004 (2006)
3	Precipitation-Frequency Atlas of the United States, Puerto Rico, and the U.S. Virgin Islands	2006 (2008)
4	Precipitation-Frequency Atlas of the United States, Hawaiian Islands	2009 (2011)
5	Precipitation-Frequency Atlas of the United States, Selected Pacific Islands	2009 (2011)
6	Precipitation-Frequency Atlas of the United States, California	2011 (2014)
7	Precipitation-Frequency Atlas of the United States, Alaska	2012
8	Precipitation-Frequency Atlas of the United States, Midwestern States (Colorado, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Oklahoma, South Dakota, Wisconsin)	2013
9	Precipitation-Frequency Atlas of the United States, Southeastern States (Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi)	2013
10	Precipitation-Frequency Atlas of the United States, Northeastern states (Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont)	2015 (2018)
11	Precipitation-Frequency Atlas of the United States, Texas	2018

In simple terms, the DDF data estimated by Atlas 14 use historical precipitation records from weather stations across a region (in the case of Volume 11–Texas) to derive probability distributions that describe the relationship between storm depth and storm frequency for storms of a *specified* duration. Storm frequency is expressed as the probability of a storm of a specified duration (e.g., 24 hours) occurring annually. The resulting probability distributions can be used to estimate the average time (in years) between storm events, or the annual probability of a storm event, for storms of a specified duration and depth (the difference in expression of frequency depends on the exact methodology used, and is discussed later in this section).

DDF probability distributions are derived by constructing AMS from individual weather stations. The AMS is constructed by extracting the largest rainfall depth from each year of the historical precipitation record of a location. Probability distributions are then fit to the AMS. In Atlas 14 and previous DDF studies, L-moment methodology is used to derive probability distributions from the AMS. L-moment methods have been found to be a more stable and accurate method for fitting probability distributions than conventional moment or maximum likelihood estimation, but the probability distributions that result from either method are identical in form and function. After assessing goodness of fit of several different probability distributions to the AMS, the Atlas 14 team used the General Extreme Value (GEV) distribution to model all storm durations. Monte-Carlo simulations based around the fitting process were also used to derive confidence intervals on the probability distributions, and therefore the precipitation estimates.

The AMS probability distributions quantify the maximum rainfall depth expected at a location over a continuous range of frequencies (probabilities between 0 and 1) and for a single specified (modeled) storm duration. The AMS probability distributions are then used to estimate the maximum depth of precipitation for storms of a specified duration (e.g., 24 hours) and for any specified frequency (e.g., 1 percent or 1 year out of every 100). This information, describing the precipitation depths for combinations of storm duration and frequency, is the DDF data reported by the Atlas 14 project. Atlas 14 models and reports storm durations between 5 minutes to 60 days and reports AMS depths for frequencies between 2 to 1000 years[2] (Table 3).

Regionalization

As in other Atlas 14 volumes, the AMS methodology for Texas combines the precipitation records of neighboring weather stations to stabilize AMS. First, AMS are derived for individual stations. A regionalization approach is then used to group stations based on

[2] Note that AMS are only extracted for durations between 15 minutes and 60 days; durations of 5 and 10 minutes are derived indirectly from the 15-minute AMS.

geographic similarity and similarity of precipitation. The regional approach is particularly important for deriving stable estimates of precipitation depth for average recurrences that are much longer than the record length at any one station and to fill in missing records in one gauge using data from another. The regionalization method averages the L-moment statistics derived from individual stations within a regional grouping of stations.

Spatial Interpolation

The DDF probabilities derived for each station are interpolated to provide point estimates at a spatial resolution of 0.0083 decimal degrees. The Atlas 14 team used a Parameter-elevation Regressions on Independent Slopes Model (PRISM) for the spatial interpolation. The PRISM approach enables the spatial interpolation to account for consistent trends between precipitation and elevation. Spatial interpolation was performed using the Mean Annual Maxima value derived for each station and storm duration. The spatially interpolated data provide near continuous point estimates of DDF data across Texas.

Annual Maximum Series versus Partial Duration Series

Atlas 14 reports DDF data for both the AMS and Partial Duration Series (PDS). The difference between the two series are as follows:

- AMS uses the maximum rainfall event in each year of the weather record to construct a series.
- PDS uses the N highest rainfall events above a certain threshold to construct a series.

A PDS includes all the values that occur within an analysis period that are higher than a specified threshold value. The AMS provides information on the AEP of precipitation depth (for a specified duration) for any given year. The PDS provides information on the Average Recurrence Interval (ARI) or the average number of years between storm events that exceed a given depth. For frequent events (toward the 50 percent AEP or 2-year ARI), there may be considerable differences between PDS and AMS depths, but differences become negligible above frequencies of approximately 15 years. The Atlas 14 methodology uses AMS to derive probability distributions, then uses a separate conversion ratio (derived for each station) to estimate PDS depths from the AMS estimates. Atlas 14 estimates 1-year PDS precipitation depths for all storm durations in addition to the frequencies estimated using AMS.

Climate Change

As in previous Atlas 14 volumes, the Atlas 14 volume 11 team report no statistical evidence of a non-stationary climate record that would indicate symptoms of climate change. The team reached this conclusion after tests applied on Texas' AMS data did not detect statistically significant trends in over 80 percent of stations tested (stations with at least 70 years of data).

Table 3. Analysis Details for NOAA Atlas 14 Volume 11 DDF Study.

Analysis Detail	Value
Type of series analyzed	Annual Maximum and Partial Duration
Durations analyzed	2, 5, 10, 15, 30, 60 minutes; 1, 2,3,6,12 and 24 hours; and 1,2,3,5,7,10,20,30,45 and 60 days
Frequencies reported	2-, 5-, 10-, 25-, 50-, 100-, 250, 500, and 1000-year
Method of Regionalization	Nearest N Neighbors: L-coefficient of variation, L-skew
Probability Distributions Used	GEV (all durations))
Method of Spatial Interpolation	PRISM
Spatial Resolution	30 arcsec = 0.0083 decimal degrees ~ 0.5 miles
Station Coverage	Texas (with neighboring state stations)
Number of Stations:	
Subhourly	294
Hourly	478
Daily	1231
Total	2003
Years of Record:	
Subhourly	8232
Hourly	19,598
Daily	73860
Station Density (stations per 1000 square mile):	
15 minutes	10.94
Hourly	17.79
Daily	45.8

The previous descriptions provide an overview of the methods but do not capture the full magnitude and complexity of the work involved to generate reliable and accurate DDF estimates for the state. These complex methods have been developed over time by meteorologists and statisticians. Table 3 summarizes the full scope of the Atlas 14 Volume 11 methodology. The current Atlas 14 precipitation frequency estimates supersede data from the following publications/studies:

- NOAA Technical Memorandum National Weather Service HYDRO-35. Five- to 60-Minute Precipitation Frequency for the Eastern and Central United States (Frederick et al., 1977) for 5-minute to 60-minute durations.
- Weather Bureau Technical Paper No. 40. 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) for 2-hour to 24-hour durations.
- Weather Bureau Technical Paper No. 49. Two- to Ten-Day Precipitation for Return Periods of 2 to 100 Years in the Contiguous United States (Miller, 1964) for 2-day to 10-day durations.

The next section describes the methodologies and DDF data derived from these previous studies.

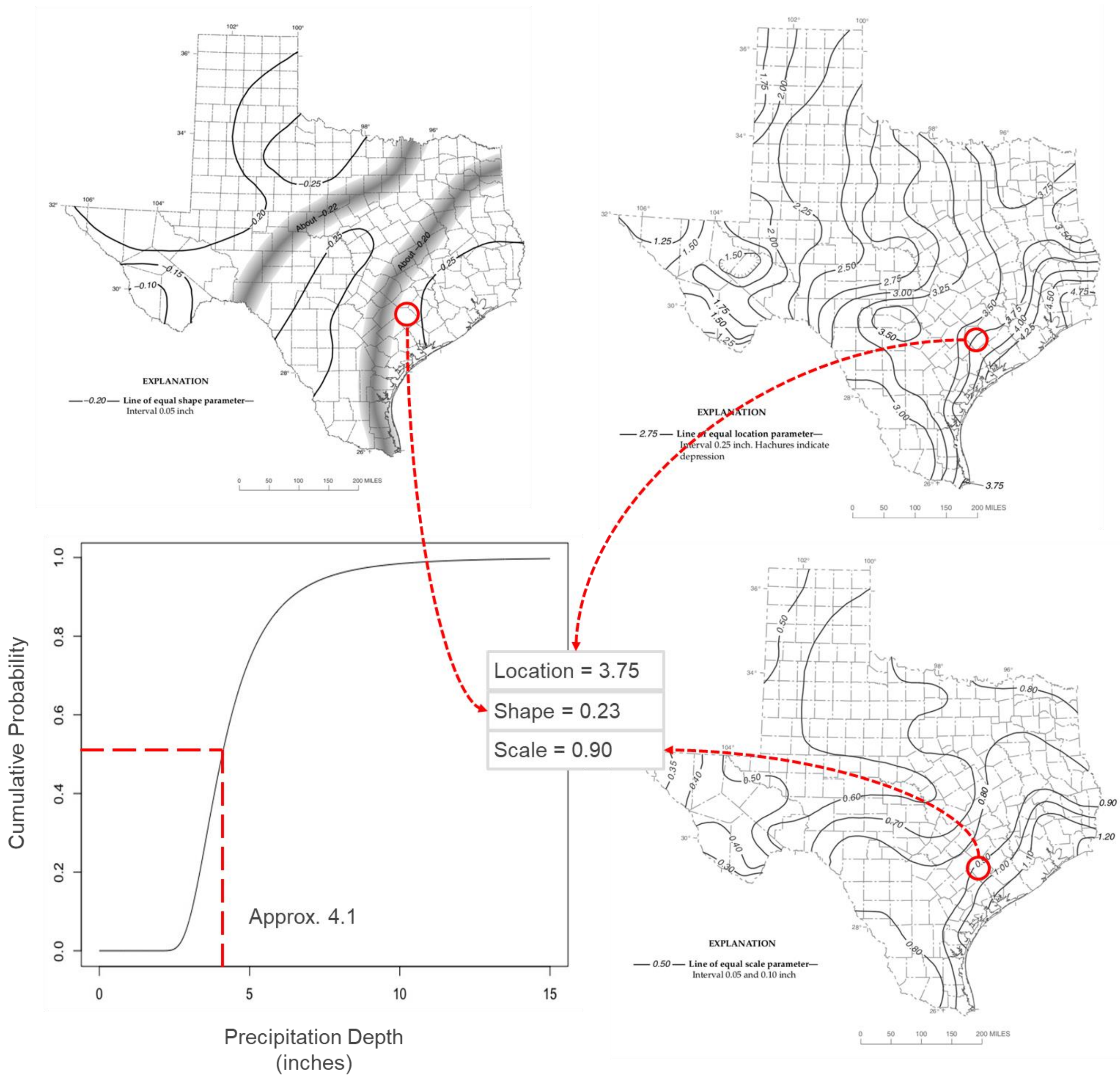
PREVIOUS DEPTH-DURATION-FREQUENCY STUDIES

Depth Duration Frequency of Texas, a Study by Asquith (1998)

Asquith (1998) documents the development of probability distributions describing storm depth for different durations and frequencies (ARIs). The study developed storm probability distributions for durations of 15, 30, and 60 minutes; 1, 2, 3, 6, 12, and 24 hours; and 1, 2, 3, 5, and 7 days. The overlap in durations of 60 minutes versus 1 hour, and 24 hour versus 1 day, occur because of the differences in depths observed by summing four 15-minute intervals versus depths observed using a single 1-hour sample interval (and similar aggregations for 60-minute and 1-day comparisons). While the 1-hour and 1-day records are collected on a fixed-interval basis, the 60-minute and 24-hour maxima are determined with four consecutive 15-minute windows or 24 consecutive 1-hour windows, respectively. These sampling issues were explored and corrected using empirically derived factors. The study analyzed annual maximum precipitation data from 1312 stations distributed across Texas. Of these, 173 recorded data at 15-minute intervals, 274 recorded data at hourly intervals, and 865 recorded data at daily intervals.

The authors used the precipitation records from each station to fit a generalized logistic (GLO) probability distribution for all durations less than 1 day. The GEV distribution was used for durations of 1 day or greater. The station-specific storm mean depth was calculated for each station. A regionalization method (using averages of the five nearest neighbor stations) was used to compute the L-coefficient of variation and L-skew values. The five-station regionalization method was chosen after experimentation with different regions of influence.

The L-moments (regionalized or otherwise) for each station were then converted to parameters (scale, location, and shape) of the GLO or GEV distributions (depending on the duration being analyzed) and then spatially interpolated (using kriging). Although not explicitly stated in the report, the kriging is likely to have generated a raster layer (also called the *parameter raster*) for each parameter set and each predicted storm duration. Finally, contour maps were produced describing lines of an equal location, scale, and shape parameter of the fitted functions for each precipitation duration. These parameter contour maps were included in the published report. Figure 3 illustrates these maps, with a demonstration of how they were intended to be used to derive a location-specific probability distribution and AEP for a specified storm duration.



Note: The maps show contours of scale, location, and shape parameters for the GEV probability distribution for 1-day storm durations. The maps enable a specific GEV distribution to be parameterized for a specified location (red circles on the maps). The distribution can then be used to estimate the storm depth for a specific ARI.

Figure 3. Examples of Contour Maps Published by Asquith (1998).

Atlas of Depth-Duration Frequency of Precipitation Annual Maxima for Texas, a Study by Asquith and Roussel (2004)

One of the problems with the maps generated by Asquith (1998) was that the parameter contour maps were difficult to use in practice. The first problem is that hydraulic engineers are most interested in the probability of storm intensity exceedance for a specified storm duration, whereas Asquith's parameter maps provide a method of estimating rainfall depth for a fixed ARI and fixed storm duration. Therefore, to obtain a depth for a specified storm duration and ARI, a user is required to read off parameters from multiple maps, construct the appropriate probability functions, algebraically estimate storm depths for each duration for a specific ARI, and then interpolate the resulting depth-duration data to find the depth for a specified storm duration. The second problem with presenting parameter contours is that spatial interpolation (by eye) of parameters between contours makes it difficult to obtain the exact set of three parameter values required to recreate the original probability distribution. In either case, the maps developed by Asquith (1998) presented considerable problems for practical use.

Asquith and Roussel (2004) extended the work of Asquith (1998) by translating the contour maps of probability function parameters to contour maps of annual maximum storm depths for the same storm durations. Instead of providing three parameters for each storm duration, the authors provided maps for 2-, 5-, 10-, 25-, 50-, 100-, 250-, and 500-year frequencies.

Figure 4 shows a flow diagram of the work conducted in the report, and indicates that the parameter rasters developed by Asquith (1998) were used to develop the 96 duration and ARI-specific storm depth contour maps. However, during the procedure of developing the new DDF contours, Asquith and Roussel (2004) found inconsistencies in duration and ARI-specific contour maps produced directly from Asquith (1998). For example, for areas of south Texas, the depth contours' duration and large recurrence intervals (50 to 500 years) were larger than the depths for the 1-day duration. In northwest Texas, the DDF values were problematic because they did not match values predicted for bordering Oklahoma that were being analyzed in a parallel study. Additional analyses were run for these regions using original station data. Figure 5 shows the 2-year, 1-hour depth contour map published in the report. Table 4 summarizes the analysis.

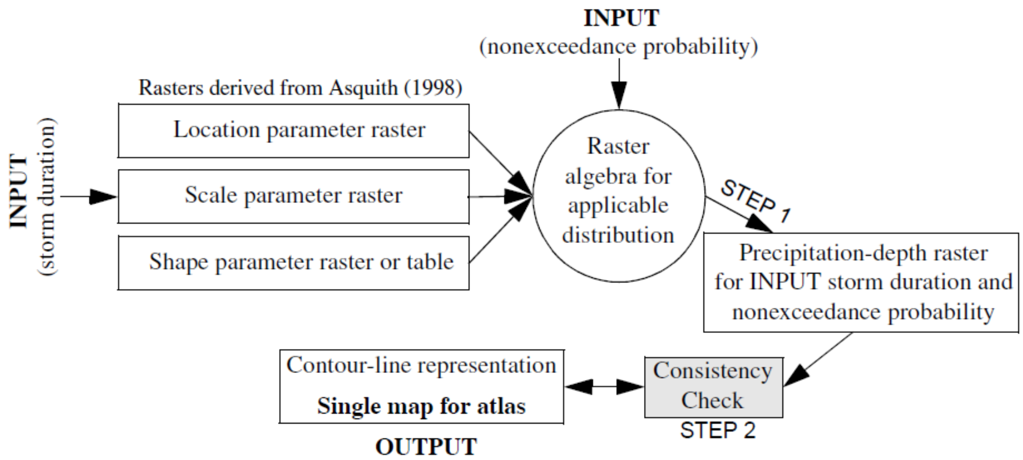
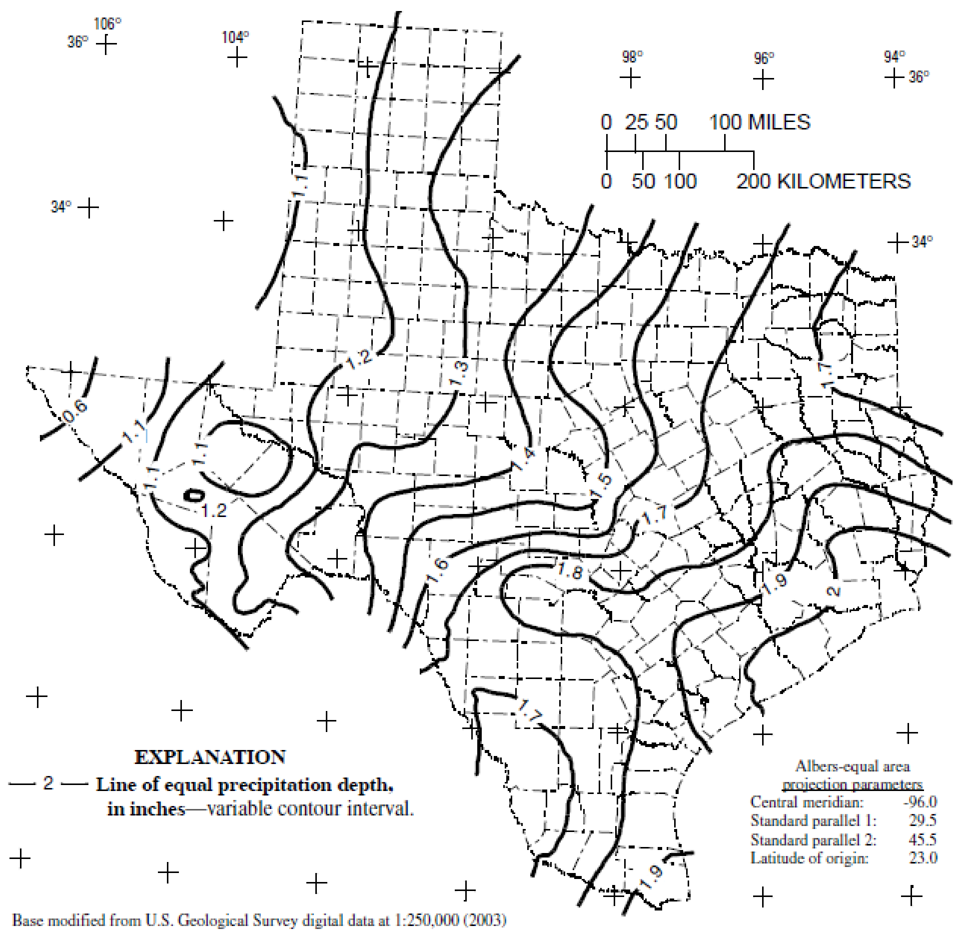


Figure 4. Flow Diagram of Work Performed during Asquith and Roussel (2004) Indicating the Use of Data from a Previous Study.



Note: Contour intervals are 0.1 inches.

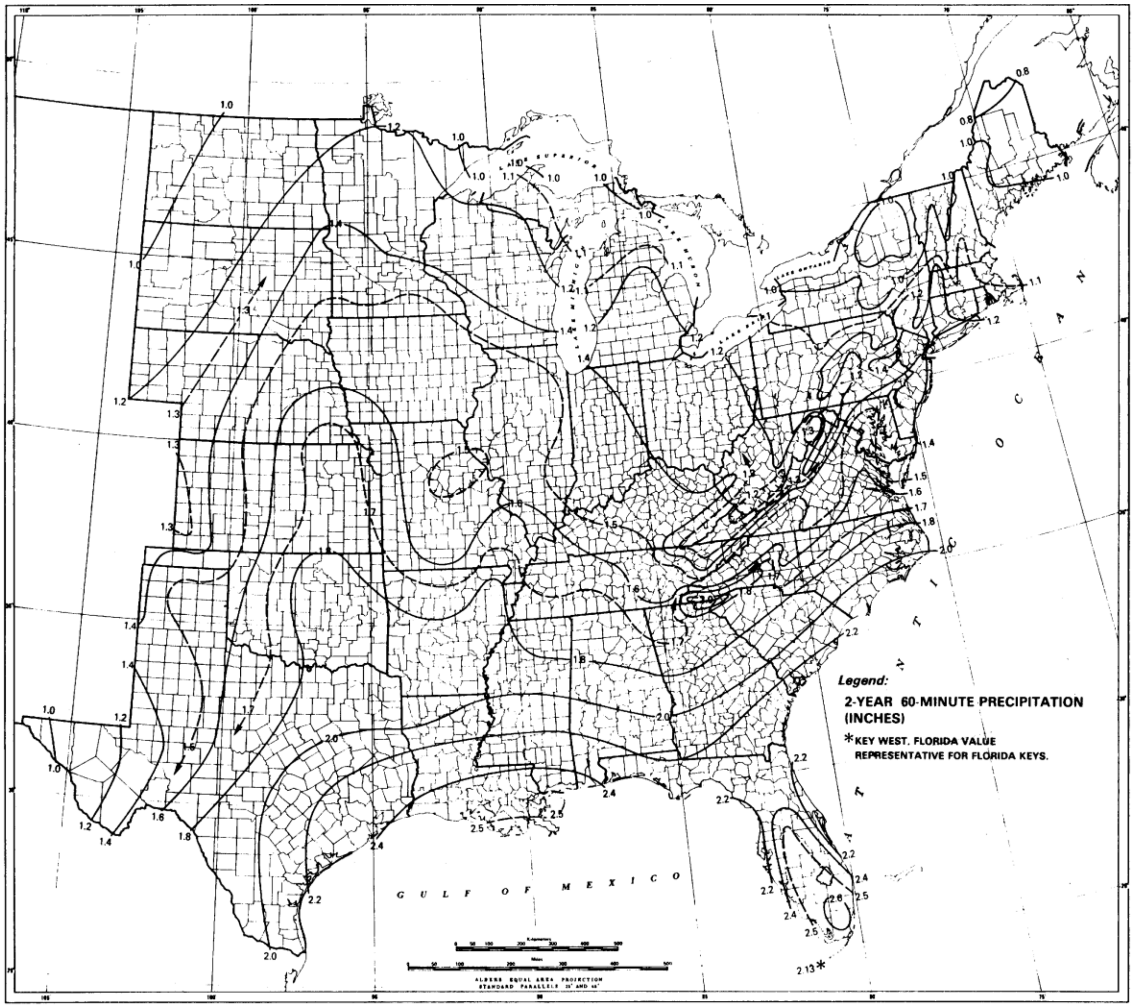
Figure 5. 2-Year, 1-Hour Precipitation Depth Contour from Atlas of DDF of Precipitation Annual Maxima for Texas.

Table 4. Summary of Analysis Details for Asquith (1998) and Asquith and Roussel (2004) DDF Studies.

Analysis Detail	Value
Type of series analyzed	Annual maximum
Durations analyzed	15, 30, and 60 minutes; 1, 2, 3, 6, 12, and 24 hours; and 1, 2, 3, 5, and 7 days
Frequencies reported	2, 5, 10, 25, 50, 100, 250, and 500 year
Method of regionalization	Nearest neighbor: L-coefficient of variation, L-skew
Probability distributions used	GLO (< 1-day durations) GEV (≥ 1-day durations)
Method of spatial interpolation	Kriging the GEV and GLO parameters
Station coverage	Texas only
Number of Stations:	
15 minutes	173
Hourly	274
Daily	865
Total	1,312
Years of Record:	
15 minutes	3,030
Hourly	10,160
Daily	38,120
Total	
Station Density (Stations per 1000 Square Miles):	
15 minutes	0.646
Hourly	1.02
Daily	3.23

Five to 60-Minute Precipitation Frequency for the Eastern and Central United States, a Study by Frederick et al. (1977)

This study presented precipitation-frequency values for durations of 5, 15, and 60 minutes at return periods of 2 and 100 years for 37 states (Figure 6). The study estimated both AMS and PDS. The study used the GEV distribution (referred to in the report as *Fisher-Tippett Type I*) to represent the AMS for each station. Probability distributions were fit to station data using the method of moments. Two-year depths (i.e., 50 percent) were used to derive the mean of the distributions, while the rations of 2-year to 100-year depths were used to determine the other parameters.



Note: Contour intervals are 0.2 inches.

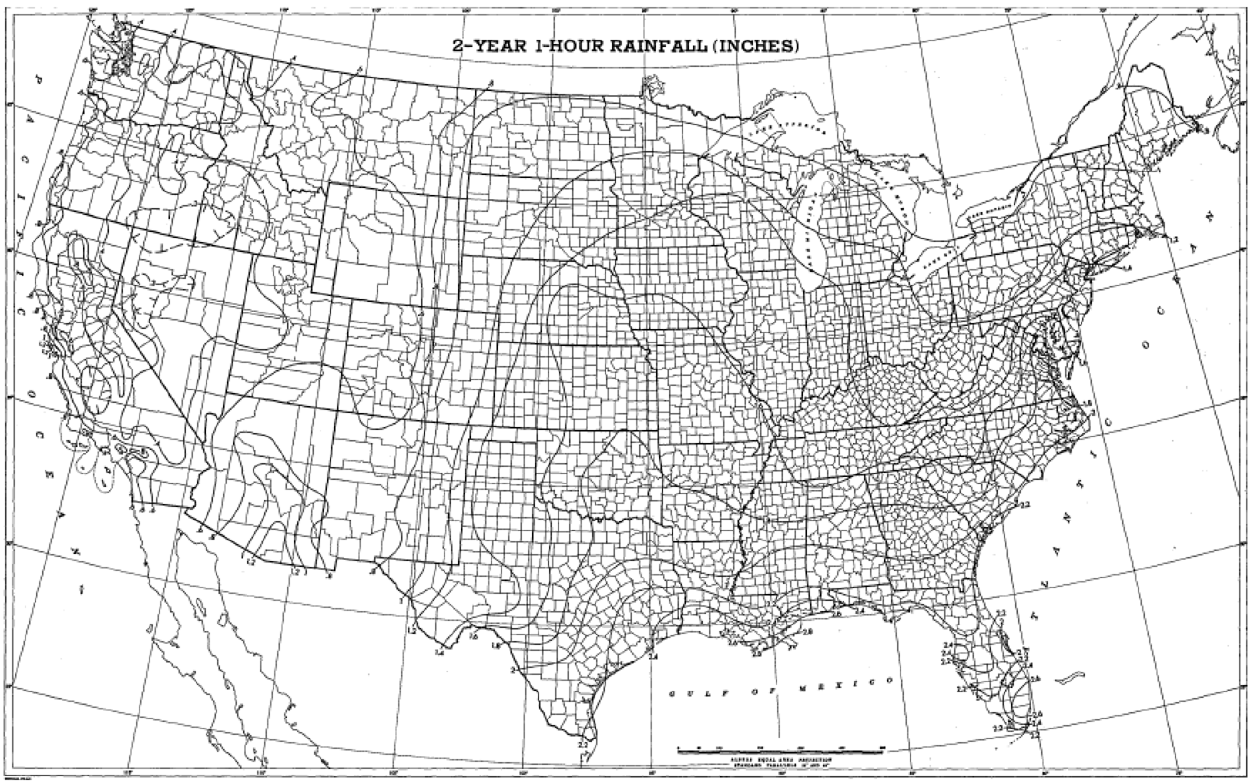
Figure 6. 2-Year, 1-Hour Precipitation Depth Contours from Five to 60-Minute Precipitation Frequency for the Eastern and Central United States.

The study used data from 200 stations collecting data at intervals less than 1 hour and from 1900 stations collecting hourly data. Factors were estimated to convert AMS to PDS (based on a subsample of stations where PDS were explicitly calculated).

The study used the fitted probability distributions to predict precipitation depth at each station for 2- and 100-year return intervals, and 5-, 15-, and 60-minute storm durations. These values were then spatially smoothed based on grouping all station data within latitude-longitude grids and iteratively correcting the depths of neighboring stations. Finally, the smoothed and non-smoothed station depths were plotted on a map, and contours were drawn manually.

Rainfall Frequency Atlas of the United States, a Study by Hershfield (1961)

In this study, rainfall depth durations and frequencies were estimated and mapped for 30 minutes, 1 hour, 2 hours, 3 hours, 6 hours, 12 hours, and 24 hours for return intervals of 1, 2, 5, 10, 25, 50, and 100 years. The study precedes microcomputers. Analysis of each station was performed graphically, and contours (spatial interpolation) were performed by hand. Analyses were performed on 200 subhourly stations, 2081 hourly stations, and 1350 daily stations. Figure 7 shows a typical DDF map published in the study (each contour shows depth increments of 0.2 inches).



Note: Contour increment are 0.2 inches.

Figure 7. 2-Year, 1-Hour Precipitation Depth Contour Map from Rainfall Frequency Atlas of the United States.

INTENSITY-DURATION-FREQUENCY STUDIES

The current *ebd* coefficients used throughout Texas are derived from TxDOT Project 0-6824, New Rainfall Coefficients—Including Tools for Estimation of Intensity and Hyetographs in Texas, by Cleveland et al. (2015). The study used DDF data from Asquith and Roussel (2004), which in turn were at least partly derived from Asquith (1998). In addition to fitting *ebd* coefficients, the study also developed an improved Excel-based tool, EBDLKUP-2015v2.1, to calculate storm intensities by county and storm duration.

Although EBDLKUP-2015v2.1 contains the current accredited coefficients, there is some confusion about their provenance. The final report of Project 0-6824 contains a list of final parameters in Appendix IV. However, these do not match the parameters contained within EBDLKUP-2015v2.1. Instead, the current *ebd* parameters are published in Appendix C of Tay et al. (2015). The two studies are related and conducted in the same laboratories. Both reports provide excellent sources of information on the history of IDF models in TxDOT and the methods used to fit the *ebd* equation to storm data.

Each study describes different methods for fitting the IDF model to DDF data. Cleveland et al. (2015) used a method based on log transforming and linearizing the IDF equation (Equation 4). In this form, linear regression can be used to estimate *e* and *b* parameters if *d* is known. Estimating *ebd* concurrently simply involves iterating over different values of *d* and then repeating the linear regression (i.e., optimizing for the *d* parameter). Cleveland advocates the predicted residual error sum of squares (PRESS) statistic as the objective function for optimization.

$$\mathrm{Log}_{10}(I_{ARI}) = \mathrm{Log}_{10}(b) - e\,\mathrm{Log}_{10}(T_c + d) \qquad \text{Equation 4}$$

Tay et al. (2015) used a nonlinear optimization function, written in the R Statistical software (package nlm). The nonlinear optimization used the sum of squares (SSQ) error as an objective function. Tay et al. (2015) produced a series of graphs and maps illustrating differences in *ebd* values derived from the two estimation methods and advocated that nlm is more straightforward to program than the linearization technique.

Assuming the objective function has a global minimum, the two methods should produce the same *ebd* coefficients. In practice, the difference in parameter estimates may occur because the optimization process does not find a global minimum (optimization for *d* in the linear case, and *e, b,* and *d* consecutively in the nonlinear case). More likely, differences in parameter estimates (using the same data) are caused by different objective functions (e.g., SSQ versus PRESS). A subtle point to consider is that in the linear version of the IDF function (Equation 4), the SSQ error is the squared difference between the logarithm of intensities (predicted and observed). In contrast, in its original form, the SSQ error is composed of the difference between non-transformed intensities (predicted and observed).

Both Cleveland et al. (1995) and Tay et al. (1995) estimated *ebd* coefficients for each of the 254 Texas counties. Neither report states *exactly* how DDF values were obtained from the Asquith and Roussel (2004) study or whether the DDF data were obtained from digitized raster surfaces, the original contour maps, or a combination of both. However, the reports do publish the original DDF data used in the analyses in appendices.

EBDLKUP-2015v2.1 Tool

Cleveland et al. (2015) developed the current EBDLKUP-2015v2.1 tool. The original version (EBDLKLUP-2015) was released in 2015. In 2016, an error in the *ebd* parameter list was found, and the tool was updated and renamed EBDLKLUP-2015v2.1.

The Cleveland et al. (2015) study updated *ebd* coefficients that dated back to 1985. The 1985 coefficients were developed and updated based on DDF data found in Hershfield (1961) and Fredrick et al. (1977). The 1985 coefficients were provided for all 254 Texas counties at ARIs of 2, 5, 10, 25, 50, and 100 years. Since the DDF contours published by the studies largely predate microcomputers and geographic information system (GIS) software, it is most likely that the coefficients were derived through graphical plots and manual interpolation of the DDF contour maps.

The first set of *ebd* coefficients were published in the 1970 Texas Department of Highways *Hydraulic Manual*. The 1970 *ebd* coefficients were derived from the 1961 publication titled *Rainfall Frequency Atlas of the United States* (otherwise known as National Weather Service Technical Paper No. 40). The 1970 coefficients provide frequencies of 5, 10, 25, and 50 years. Given the dates of the studies, the coefficients were most likely estimated using depth data manually interpolated from the continental scale contours published in the report, and then using graphical analysis of the depth-duration data.

Both the 1970 and 1985 coefficients are provided in the appendices of Cleveland et al. (2015). The 1970 coefficients are methodologically different from the 1985 or 2005 coefficients in that they use a common *d* parameter across all ARIs. The 1985 *ebd* coefficients were also incorporated into an early spreadsheet tool, EBDLKUP.xls, created circa 1998 (Figure 8).

Rainfall Intensity-Duration-Frequency Coefficients for Texas Counties

1. Select your county. 2. Enter the time of concentration

County	Coefficient	2-year	5-year	10-year	25-year	50-year	100-year
Harris	e (in)	0.800	0.749	0.753	0.724	0.728	0.706
	b	68	70	81	81	91	91
	d (mins)	7.9	7.7	7.7	7.7	7.7	7.9
	Intensity (in/hr)*	6.8	8.1	9.3	10.1	11.2	11.9
	Coefficient	2-year	5-year	10-year	25-year	50-year	100-year
	e (mm)	0.800	0.749	0.753	0.724	0.728	0.706
	b	1727	1778	2057	2057	2311	2311
	d (mins)	7.9	7.7	7.7	7.7	7.7	7.9
	Intensity (mm/hr)*	171.8	206.6	236.4	256.9	285.3	301.6
* for time of Concentration =		**10** mins					

Harris
Harrison
Hartley
Haskell
Hays
Hemphill
Henderson
Hidalgo
Hill

Figure 8. Original EBDLKUP Excel Spreadsheet Tool.

SUMMARY

The need for accurate, statewide storm data has resulted in considerable research into the analysis of weather station data to provide estimates of the probability of storm events of various durations. In turn, these data have been translated into IDF models more useful for hydraulic design. These IDF models provide a storm intensity for a specified storm duration (t_c) and storm frequency.

Data provided through the Atlas 14 project are derived from nearly twice as many stations and precipitation records than were used to derive previous DDF data for the state. The Atlas 14 data also benefit from improvements and additions to methodology, which include improved method of spatial interpolation and estimation of PDS DDF data.

Since IDF models are developed from DDF data, many of the errors and assumptions associated with analyzing precipitation data will also be transferred to the *ebd* coefficients. The analysis of DDF data is complex and demanding, and has traditionally been a cooperative effort among various agencies. In the past, TxDOT has sponsored such initiatives and continues to be involved through Atlas 14. Outsourcing these complex DDF analyses is useful and probably essential. However, it is also important to understand IDF models and parameters in the context of assumptions and errors associated with the original DDF analysis.

CHAPTER 4. METHODS FOR CALCULATING *EBD* VALUES

This chapter describes the procedures used throughout this project for estimating *ebd* coefficients from Atlas 14 precipitation data.

ESTIMATING *EBD* COEFFICIENTS

The method used to estimate *ebd* coefficients in this study is based on those presented by Cleveland et al. (2015) (Equation 4). This method log-transforms and therefore linearizes the IDF function defined by Equation 2. In this form, a simple linear regression can be used to estimate *e* and *b* parameters for any *assumed* value of *d*. To estimate *e, b,* and *d* concurrently, the linear regression is repeated while iterating over different values of *d* (i.e., optimizing for the *d* parameter).

Cleveland et al. (2015) advocated the PRESS statistic as the objective (cost) function for fitting coefficients to the data. The Texas A&M Transportation Institute (TTI) researchers explored the use of the PRESS statistic and the simpler SSQ statistic but found minimal differences between parameter estimates. On balance, and opting for simplicity, the TTI team used SSQ as the objective function when estimating *ebd* coefficients.

SPATIALLY REPRESENTATIVE *EBD* COEFFICIENTS

One of the objectives of this research was to explore the practical utility of replacing county rainfall zone boundaries with smaller rainfall zones that take advantage of the spatial resolution of Atlas 14 data and, in doing so, improve the accuracy of hydraulic designs.

Currently TxDOT uses *ebd* values estimated for 254 Texas counties. Rainfall patterns within a county may vary considerably due to topography changes, proximity to waterbodies, or large-scale geographic trends in climate. In this sense, the *ebd* values for a specific county or more generally any defined region are intended to be *representative* of the actual rainfall characteristics of that region. That is to say, they represent some average or typical pattern of rainfall found within a defined region.

Conceptually, several ways of developing rainfall coefficients are spatially representative. One solution is to base the *ebd* fitting procedure on rainfall intensities estimated at the geometric centroid of a region. Another solution is to base the estimate on the mean (or other average) rainfall intensities within a region. The centroid method is computationally simple, but geometric centroids can occur outside unusually shaped polygons. Additionally, centroids may coincide with unusual intensity values, such as a mountain peak, affecting their overall representativeness of a region.

In this study, researchers used the spatial average rainfall intensity for a region to fit *ebd* coefficients. Although this method requires more computation, it ensures stable, representative values of rainfall intensities that are minimally affected by unusual topographic features in a region. Figure 9 clarifies this approach. First, a region is spatially defined, such as by a county boundary. Second, for a given storm frequency and duration(s), all geographically distinct rainfall intensities within the region are averaged (arithmetic mean). If the polygon that defines the region has holes, they are correctly accounted for in the averaging procedure. Third, the mean rainfall intensity for each storm duration (of a given ARI) is used to estimate the *ebd* coefficients using Equation 4.

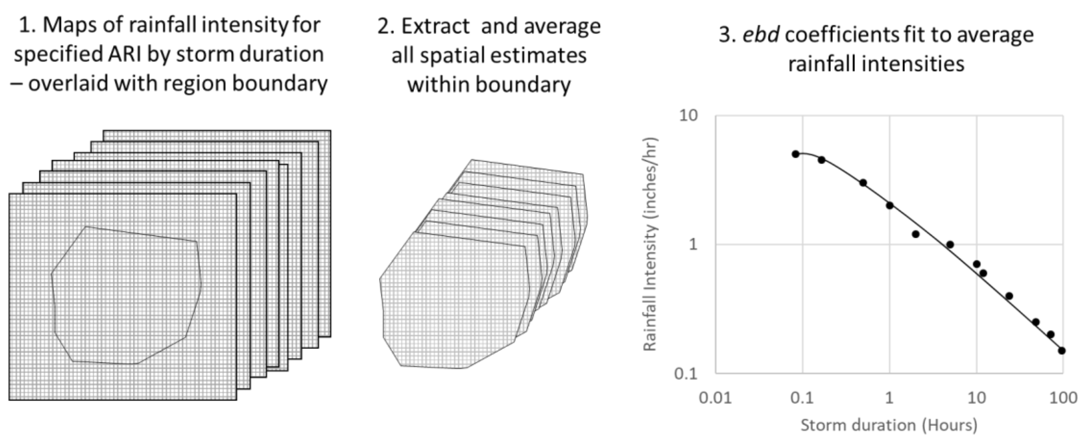


Figure 9. Steps for Extracting Spatially Representative Precipitation Intensities for a Given Region and for Fitting Spatially Representative *ebd* Coefficients.

Another advantage of using a spatially explicit approach is that it leads to useful metrics for quantifying the spatial variation within a proposed region. Researchers used the concept of spatial error to quantify how representative the mean precipitation within a region is to the range of precipitation values found in a region. For any ARI and storm duration, spatial error is defined as:

$$Spatial\ Error_{ARI,duration}\ (\%) = \frac{0.5*(I_{max}-I_{\min})}{I_{mean}} *\ 100 \qquad \text{Equation 5}$$

Where I_{max}, I_{min}, and I_{mean} are the maximum, minimum, and mean precipitation intensities, respectively, within a region. Equation 6 measures the percent difference between the minimum or maximum precipitation in a region (or more precisely, half the range) as a percentage of the mean zonal rainfall intensity. For example, if a region has a spatial error of 10 percent, then the maximum difference in rainfall intensity between any point within the region will be no more than 10 percent of the mean value calculated for that region.

OTHER ANALYSIS DETAILS

The Atlas 14 study provides depth-duration estimates for storms of a duration of 2, 5, 10, 15, 30, and 60 minutes; 1, 2, 3, 6, and 12 hours; and 1, 2, 3, 5, 7, 10, 20, 30, 45, and 60 days; and of a frequency of 1, 2, 5, 10, 25, 50, 100, 250, 500, and 1000 years. Researchers used storm duration data between 5 minutes and 72 hours (3 days) to fit *ebd* coefficients.

ANALYSIS WORKFLOW

The Atlas 14 data sets are archived on the NOAA Precipitation Frequency Data Server (https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html). The server allows users to access the data in various formats. The simplest way to access the data is through the web-based GIS interface, which enables a user to click on a location of interest to retrieve point estimates for precipitation depth.

In addition to the simple point-and-click interface, NOAA also provides several options to download the data automatically:

1. Web-based GET queries. GET queries allow users to embed longitude, latitude, and other parameters into a Uniform Resource Locator (URL). The URL is then submitted to the server, which in turn downloads the data to the client machine submitting the request. This method is often referred to as *web scraping*. The Atlas 14 website provides specific instructions on constructing the correct URL format to retrieve the demanded data. Modern programming languages (e.g., R-statistical or Python) make it easy to write small programs that allow such URLs to be generated automatically. For example, a program can be written to read a text file containing a list of locations (specified by longitude and latitude pairs), generate and submit a sequence of URL queries, and organize the data on a client computer.

2. <u>GIS grids via File Transfer Protocol server access.</u> Atlas 14 data are also available in GIS (spatial) data format, which is available for download through a File Transfer Protocol server. Each grid presents a single data variable represented in a 30 arcsecond × 30 arcsecond raster in American Standard Code for Information Interchange grid format. In other words, each grid contains a precipitation depth estimate for a specific rainfall intensity, return interval, and either partial or annual series analysis. Because the grids are named using a specified convention (documented on the website), programs can easily be written to download grids sequentially using the web-scraping method.

TTI researchers developed code to automatically download data from the Atlas 14 server. After some preliminary experimentation, TTI researchers developed an analysis workflow around downloading GIS grids to local computers and developing spatially explicit GIS analysis around these grids. The GIS grids are saved to a single folder on a local machine and converted to geoTIFF files. GeoTIFF files have faster load times (i.e., data retrieval) than the original ASCII grid format. R-code was developed to query the data by longitude and latitude (a point query) or by a defined region (i.e., a polygon).

Fitting *ebd* Coefficients

Cleveland et al. (2015) detail a robust method for estimating *ebd* coefficients from DDF data using Equation 4. TTI researchers adapted this method to estimate *ebd* coefficients from the regional or point-specific rainfall depth data retrieved from the Atlas 14 GIS grids. R-code was chosen for the fitting process because of its built-in statistical support.

The following pseudocode describes the steps for depth-duration data specific to an ARI:

1. Transform rainfall depth (inches) to intensity (inches/hour) by dividing by storm duration (in hours).
2. Log_{10} transform rainfall intensity.
3. Use the linearized version of the IDF function (Equation 4) to estimate *e*, *b*, and *d* as follows:
    a. Choose a starting value for the parameter *d* (e.g., 0).
    b. Log_{10} transform (t_c+d) according to Equation 4, and use linear regression to derive a slope and intercept parameter, equivalent to *e* and *b*, respectively. Return fitted parameters and SSQ error (or PRESS statistic) from the linear regression to the controlling function.

c. Repeat step b using a single parameter optimization routine to find the *d* value with the lowest error. The fitted *b* and *e* values with the optimized *d* value are the resulting parameters.

Researchers used the SSQ error term to estimate the *ebd* coefficients throughout the project.

Deriving *ebd* Coefficients for Multiple Locations

TTI researchers developed R-code to estimate *ebd* parameters for regions defined in GIS files (shapefiles). For example, a shapefile detailing county boundaries is used to estimate *ebd* coefficients representative of county boundaries, based on spatial averages of rainfall intensities within each boundary.

Graphs and Maps for Quality Assurance and Analysis

All fitted parameters are output to flat file formats that can be subsequently organized into relational databases or used as inputs to other R-programs for analysis. The workflow automatically generates standardized graphs showing the Atlas 14 intensity data with the fitted models.

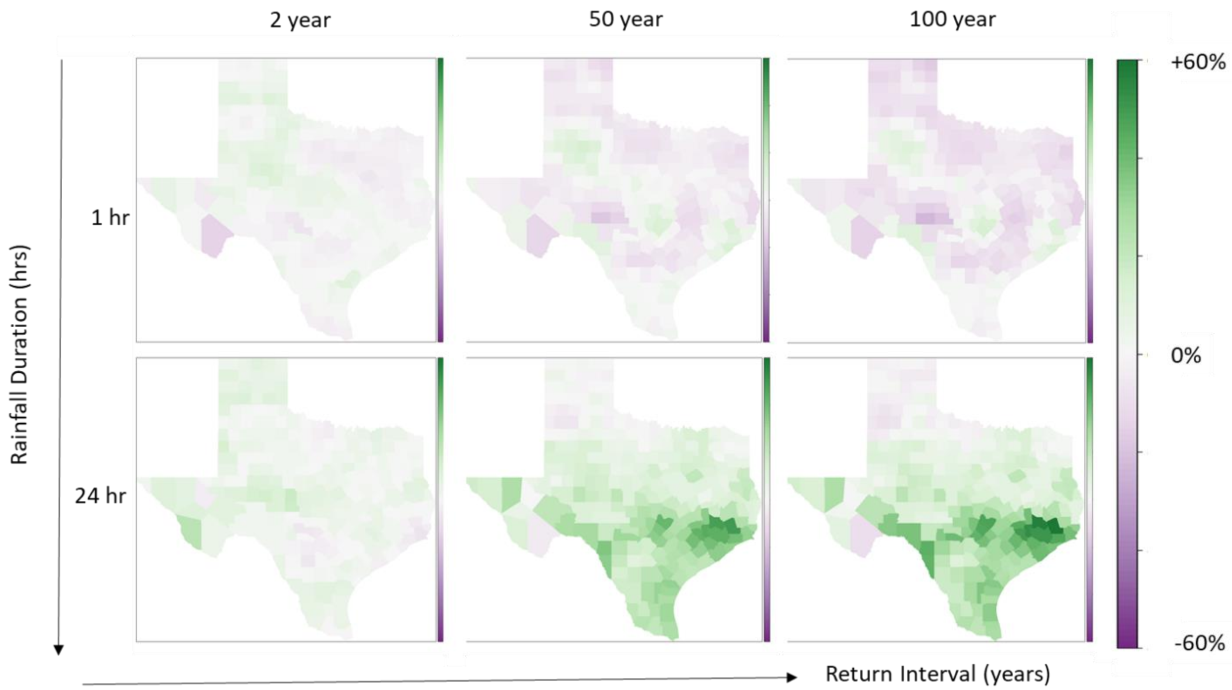
CHAPTER 5. ANALYSIS OF ATLAS 14 DATA RAINFALL PATTERNS

The *ebd* parameters currently used by TxDOT were derived from 2004 U.S. Geological Survey (USGS) Scientific Investigations Report 2004-5041, titled *Atlas of Depth-Duration Frequency of Precipitation Annual Maxima for Texas* (Asquith and Roussel 2004), which was an extension of a previous analysis by Asquith (1998). The Atlas 14 data for Texas (Volume 11) were made available to the research community in late 2018 (the report detailing the data analysis methods was formally released in early 2019). The Atlas 14 project provides improved precipitation data brought about by increases in the number of weather stations, improvements in the temporal resolution of precipitation data, and a longer climate record than that in 1998. The Atlas 14 project also incorporates a spatial interpolation method that delivers DDF data at a resolution of 30 arcseconds (approximately 0.008 decimal degrees or 0.5 miles).

This chapter analyzes differences between rainfall intensity predictions using the current TxDOT *ebd* coefficients versus predictions made using county-level *ebd* values derived from the new Atlas 14 data.

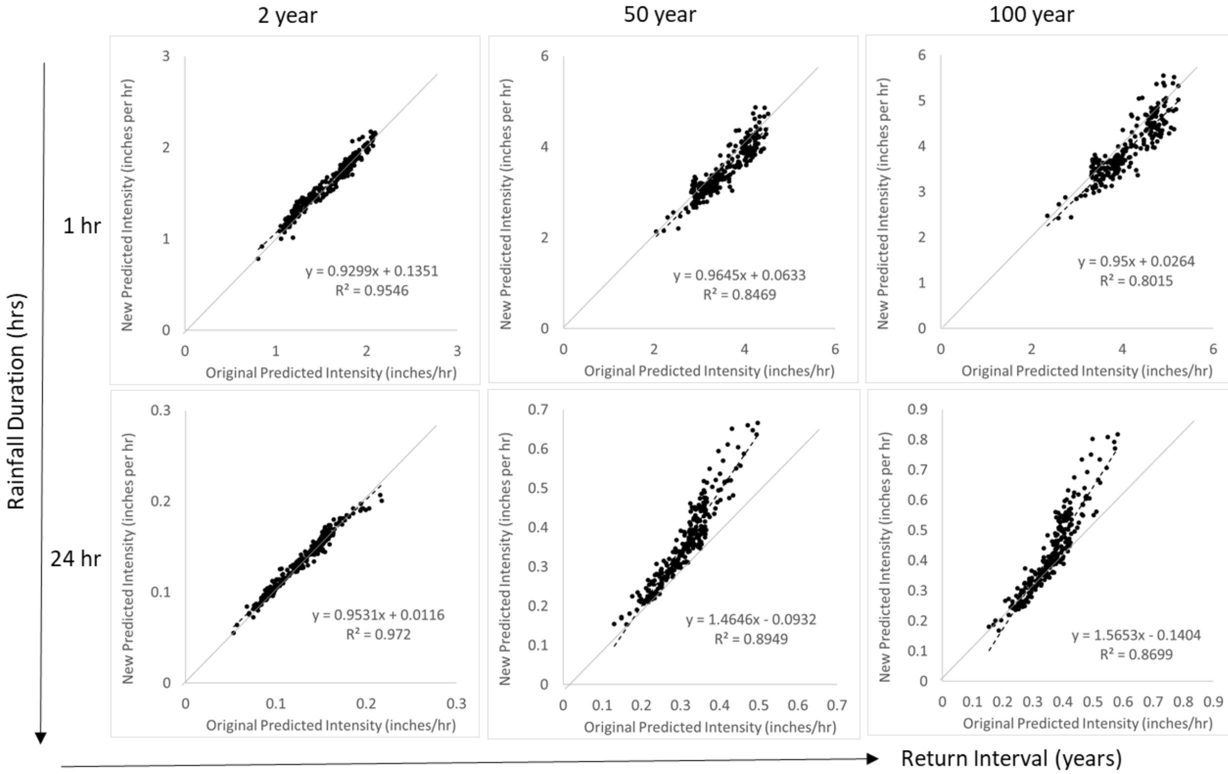
DIFFERENCES BETWEEN ATLAS 14 AMS *EBD* COEFFICIENTS AND THE CURRENT COEFFICIENTS

Figure 10 illustrates differences in rainfall intensities predicted using Atlas 14–derived *ebd* coefficients relative to predictions made using the current TxDOT *ebd* coefficients. The maps show the difference between predicted intensities as a percentage of the predicted intensity using the current *ebd* parameters. Figure 11 shows the results of the same analysis illustrated using scatter plots. Each graph in Figure 11 plots the intensity predicted using the current *ebd* coefficients (x-axis) against the intensity predicted using Atlas 14–derived *ebd* coefficients. Each plot also includes a linear regression fit to the 254 points. The linear regression slope, intercept, and R^2 coefficient indicate the extent to which the Atlas 14 predictions differ from the current *ebd* predictions. The grey line in each plot shows the 1:1, perfect correlation that would occur if both sets of parameters predicted the same values for each county.



Note: The maps show predictions for 2-, 50-, and 100-year ARIs and durations of 1 and 24 hours. The colors on the maps show the percent difference between the county-level prediction using Atlas 14 data versus current *ebd* coefficients. Green shadings illustrate counties where Atlas 14 data predict higher rainfall intensities. Purple shadings illustrate counties where Atlas 14 data predict lower rainfall intensities than the current *ebd* coefficients.

Figure 10. Maps of Rainfall Intensities Predicted by Atlas 14 AMS Data versus Existing *ebd* Coefficients.

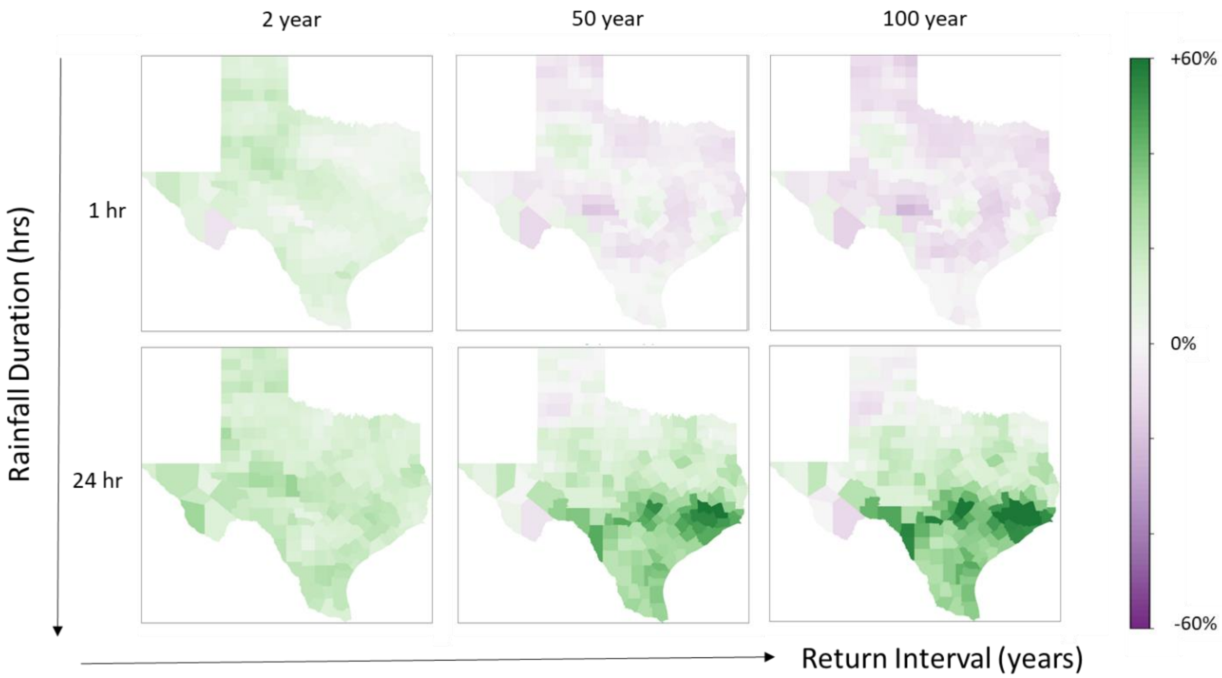


Note: For each county, intensities predicted from the existing parameters are plotted on the x-axis, with intensities predicted from newly fitted parameters on the y-axis (N = 254). Each graph also shows a linear trend line fitted to the data (plus equations and R2). The solid grey line shows a perfect 1:1 relationship that would occur if both *ebd* coefficients set predicted equal intensities.

Figure 11. Difference between Atlas 14 AMS versus the Current *ebd* Coefficients.

Figure 10 and Figure 11 show that for short rainfall durations the Atlas 14–derived *ebd* coefficients tend to slightly under predict compared to the existing *ebd* coefficients. However, for longer-duration events, Atlas 14–derived parameters tend to predict higher rainfall intensities than the existing *ebd* coefficients, especially for counties in southeast Texas.

Figure 12 shows the difference in rainfall intensity predicted using Atlas 14 partial duration data relative to predictions made using the current *ebd* coefficients. Figure 13 shows the same information graphically. For 2-year ARIs, *ebd* parameters derived from Atlas 14 partial duration data predict higher intensities than the current *ebd* coefficients across almost all counties. For longer ARIs, predictions using the Atlas 14 partial duration *ebd* coefficients tend to follow the same trends as the AMS but are generally higher.



Note: Green shadings illustrate counties where Atlas 14 data predict higher rainfall intensities. Purple shadings illustrate counties where Atlas 14 data predict lower rainfall intensities than the current *ebd* coefficients.

Figure 12. Maps of Rainfall Intensities Predicted by *ebd* Coefficients Derived from Atlas 14 PDS Data versus Existing *ebd* Coefficients.

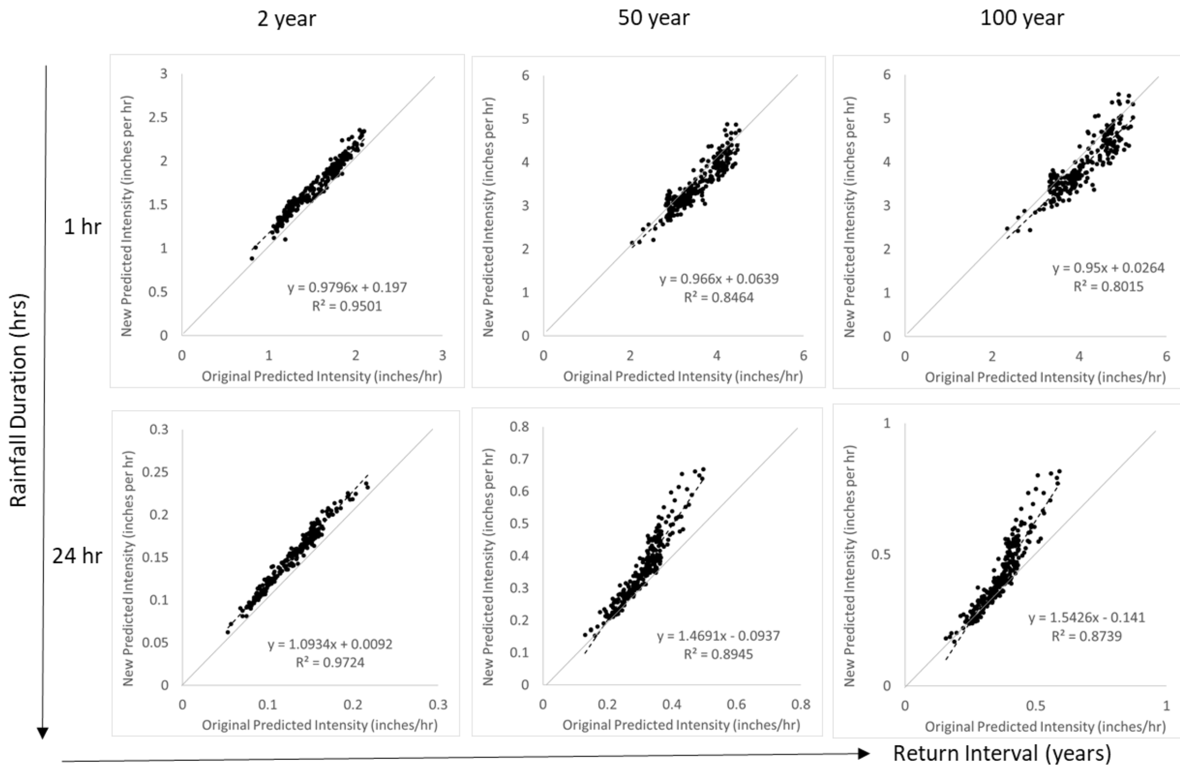
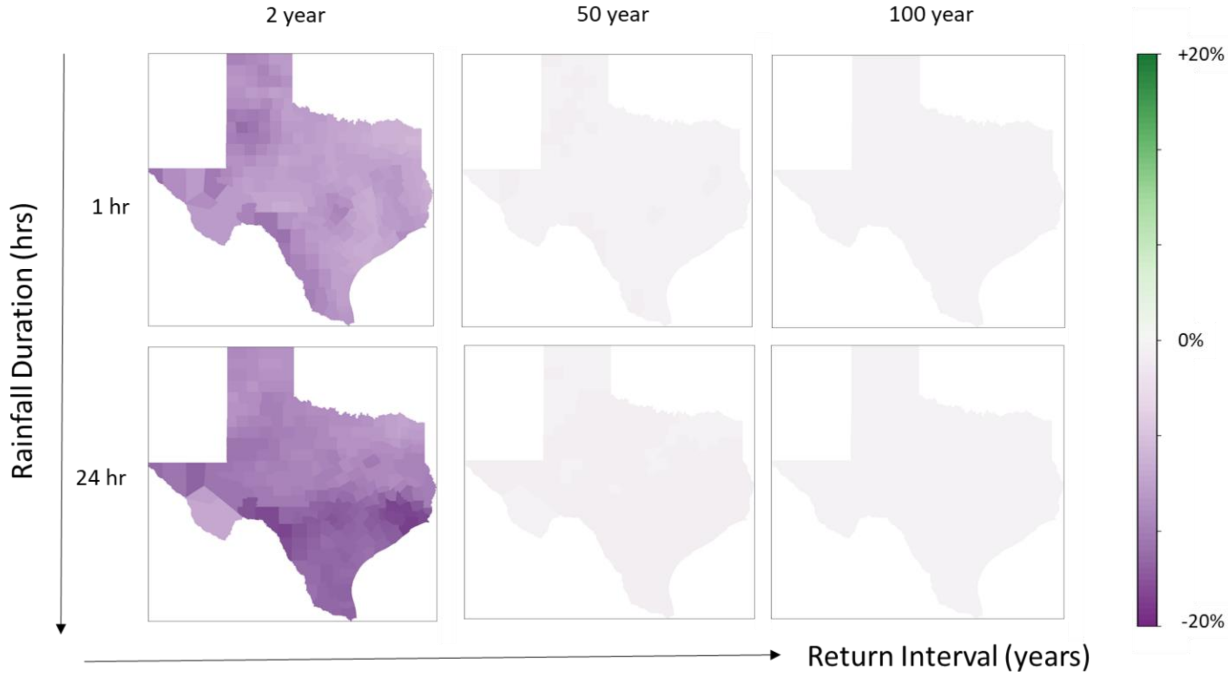


Figure 13. Difference between Atlas 14 PDS versus the Current *ebd* Coefficients.

DIFFERENCE BETWEEN ATLAS 14 AMS- AND PDS-DERIVED *EBD* COEFFICIENTS

Figure 14 shows the difference in intensity predictions using Atlas 14 AMS versus PDS data. The maps show annual series depths and partial series depths. At 2-year frequencies, the PDS predicts higher intensity rainfall than the AMS. For 50-year storm frequencies, the differences between partial and annual predictions are minor. Figure 15 shows the same information graphically. This is consistent with the Atlas 14 methodology, which transforms AMS data to PDS data using fixed ratios. Based on a review of Atlas 14 methods (e.g., Bonnin et al., 2011; Perica et al., 2014; Perica et al., 2013), as storm frequency approaches approximately 100 years, the differences between PDS and AMS estimates tend toward zero.



Note: The colors on the maps show the percent difference between county-level prediction (AMS and PDS). Green shadings illustrate counties where AMS data predict higher rainfall intensities. Purple shadings illustrate counties where PDS data predict higher rainfall intensities than AMS.

Figure 14. Maps of Rainfall Intensities Predicted by the *ebd* Coefficients Derived from Atlas 14 PDS versus AMS Data.

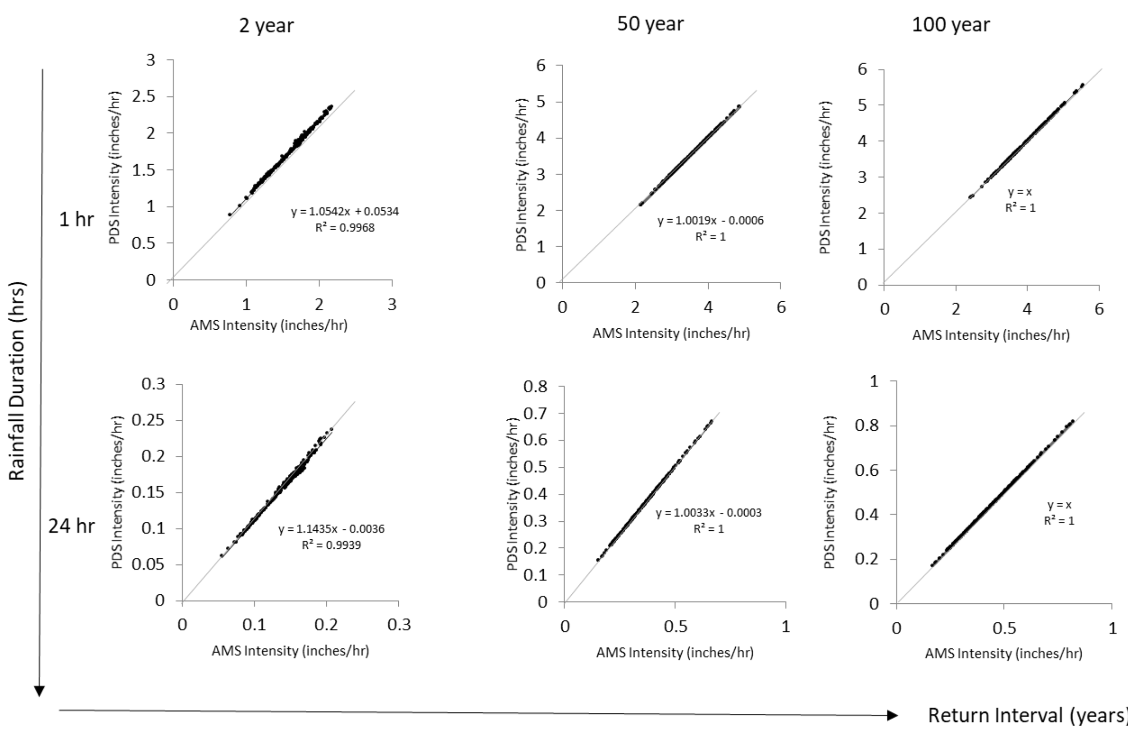


Figure 15. Difference between Atlas 14 AMS- versus PDS-Derived *ebd* Coefficients.

SUMMARY

This chapter presents and discusses the differences between the new and existing *ebd* predictions. As discussed in this chapter, the key differences are as follows:

- Across all storm frequencies and durations, storm intensities predicted by the new, provisional Atlas 14 coefficients are broadly similar to those predicted by the current TxDOT *ebd* coefficients. Exceptions occur for Gulf Coast counties, where the new Atlas 14 *ebd* coefficients predict higher intensities than the existing coefficients, especially for longer return frequencies.
- The differences between predictions from PDS *ebd* coefficients and AMS *ebd* coefficients are small, except for high probability storm events (e.g., 2-year ARIs). The agreement between the two predictions can be traced back to the methods (ratios) used to derive PDS depths from an AMS-based analysis.

CHAPTER 6. DELINEATING TEXAS RAINFALL ZONES

Chapter 4 discusses mathematical and statistical methods for deriving spatially representative *ebd* coefficients from the Atlas 14 DDF data. Currently, the TxDOT hydraulic design method uses county-level rainfall zones; that is, the *ebd* coefficients used in TxDOT hydraulic design are intended to be spatially representative of rainfall patterns in each Texas county. This chapter investigates methods for redefining rainfall zones from county zones to subcounty regions. Subcounty delineations are feasible because of the improved spatial accuracy of the Atlas 14 data relative to data that were used to derive TxDOT's current *ebd* coefficients (Asquith and Roussel, 2004).

County rainfall zones are currently used for several reasons:

- The county delineation allows engineers to easily georeference a project and thereby obtain *ebd* predictions relevant to their location.
- A relatively small number of rainfall zones makes it easier for designs to be checked and audited.
- The current TxDOT *ebd* parameters were estimated using low-resolution rainfall DDF data. Therefore, county rainfall zones represent a pragmatic way of translating low-resolution spatial data into consistent, standard methods for estimating IDF values.

The disadvantage of using county rainfall zones is that the spatial variation of rainfall within some counties may be large. In other words, a single rainfall intensity value or set of *ebd* coefficients may not be able to *accurately* or *adequately* represent the variation in rainfall throughout that county.

Chapter 4 introduced the idea of spatial error (Equation 5). This spatial error provides a measure of the variation in rainfall intensities across a delineated region for a given storm duration and frequency. In a practical context, this spatial error can be interpreted as the maximum percentage difference between a representative rainfall intensity value and the maximum and minimum intensities within the region. This spatial error is relevant to a storm of a specified duration and frequency. The idea can be extended to provide an overall spatial error for a region, evaluated for every combination of storm frequency and duration:

$$Spatial\_Error_{max} = max(Spatial\_Error_{ARI,duration})$$ Equation 6

Where:

- $Spatial\ Error_{max}$ is the maximum spatial error evaluated for a subset of storm frequency and duration combinations.
- $Spatial\ Error_{ARI,duration}$ is the spatial errors evaluated for a specified storm frequency (ARI) and duration.

TTI researchers used these concepts to investigate the effect of using different rainfall zones within Texas. In the first step of this investigation, TTI researchers evaluated the maximum spatial error ($Spatial\ Error_{max}$) associated with using rainfall zones based on county boundaries. In the second step, researchers developed an algorithm to split Texas counties into subcounty rainfall zones based on the idea of achieving a specified maximum spatial error within each county.

COUNTY-LEVEL SPATIAL ERROR

The maximum spatial error was calculated for 254 Texas counties. GIS shapefiles of county boundaries were used to extract all Atlas 14 DDF rainfall depths that fell within the county boundary. PDS grids were used as the base DDF data. The extraction process was performed on each county and for storm durations of 5, 10, 15, and 30 minutes, and 1, 2, 3, 6, and 12 hours; and storm frequencies of 2, 5, 10, 25, 50, and 100 years. The maximum duration of 12 hours was selected because the *ebd* equation is intended to be used in the Rational Method, which has been generally determined to be applicable for areas smaller than 200 acres where the t_c is not likely to exceed 12 hours.

For each county, the mean, minimum, and maximum rainfall depths were estimated and converted to rainfall intensity by dividing by storm duration. For each storm duration and frequency pair, the mean, minimum, and maximum rainfall intensities were used to calculate spatial error using Equation 6. Finally, the maximum spatial error (across all storm durations and frequencies) was calculated for each county (Equation 7).

Figure 16 shows a map of the maximum spatial error associated with each county. Figure 17 and Figure 18 graph the spatial errors for each county (each county is plotted on the x-axis, ordered by the size of spatial error).

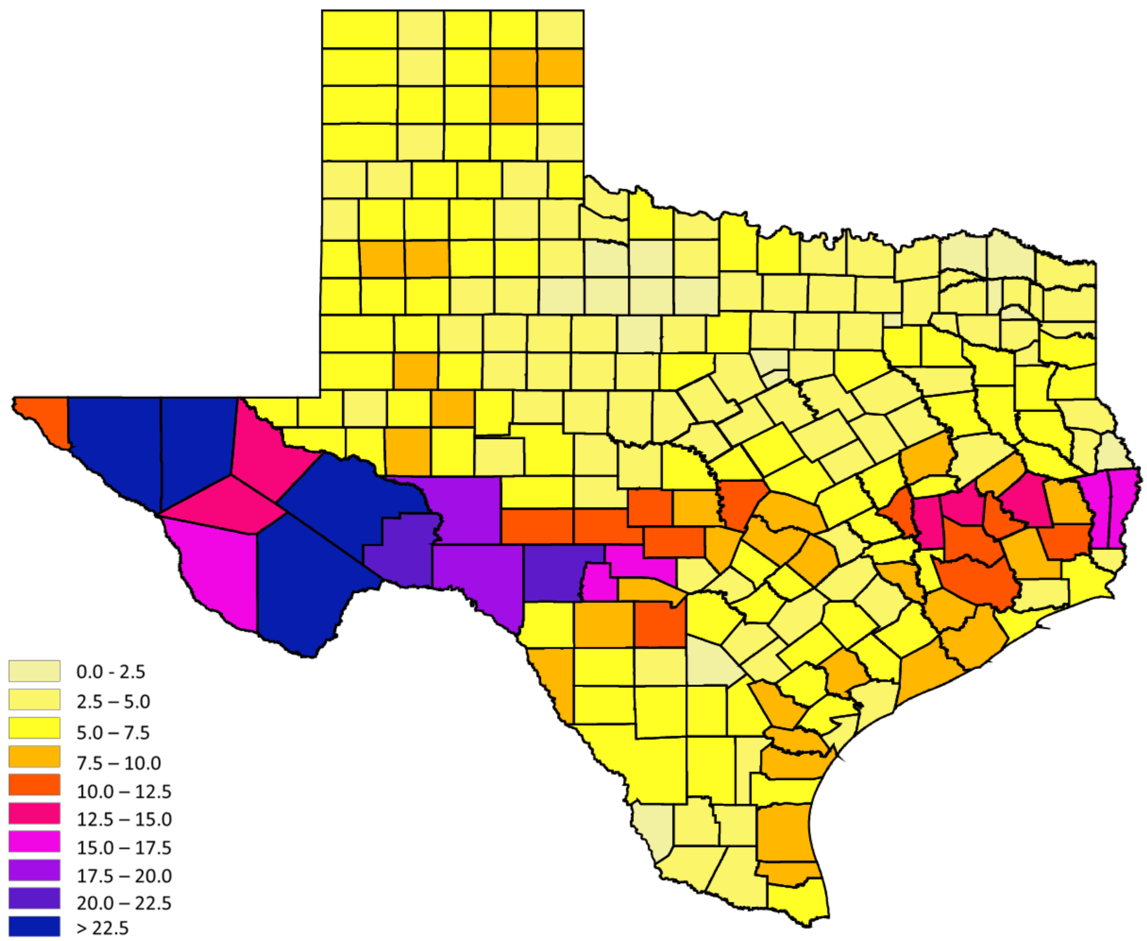
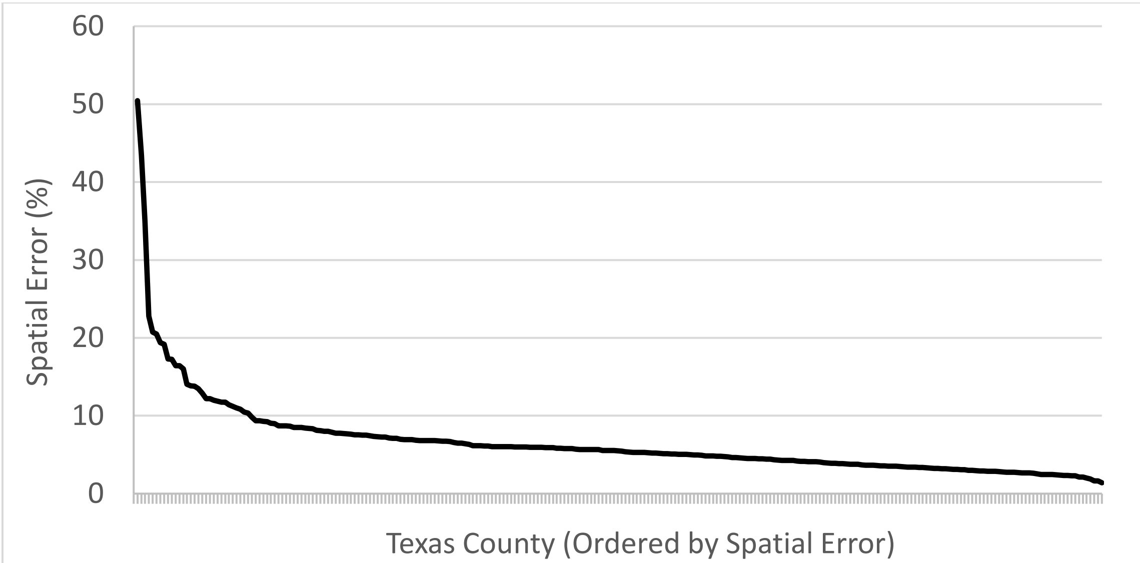


Figure 16. Maximum Percentage Variation in Storm Intensities within Texas Counties Measured across All Storm Durations and Frequencies.



Note: The counties (x-axis) are ordered by spatial error.

Figure 17. Maximum Spatial Error of Each Texas County (N=254) Evaluated for Storm Durations between 5 Minutes and 12 Hours, and Storm Frequencies between 2 and 100 Years.

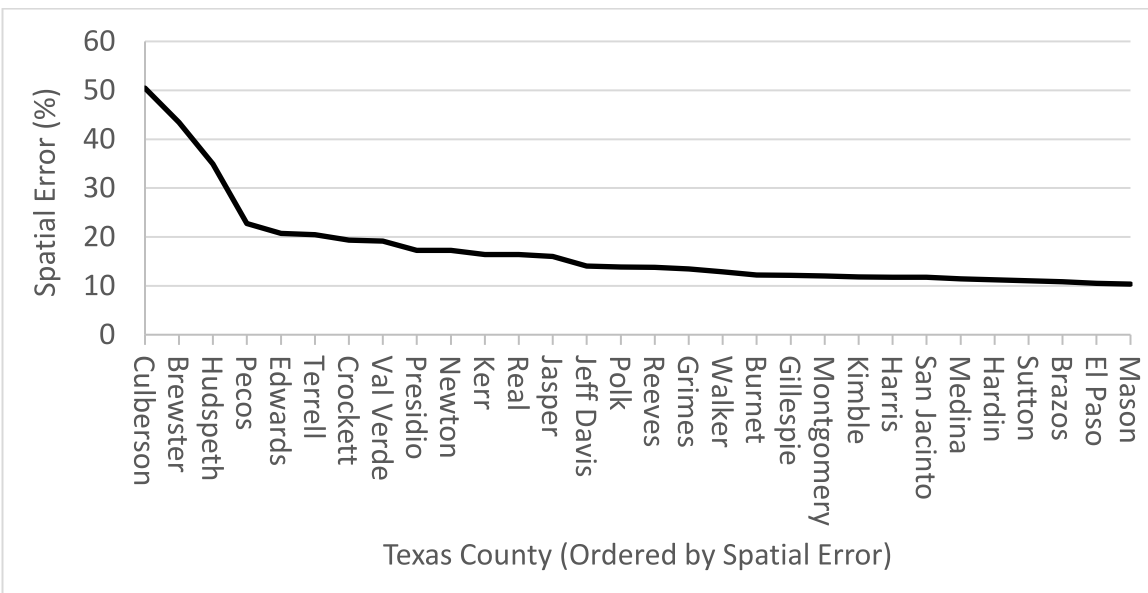
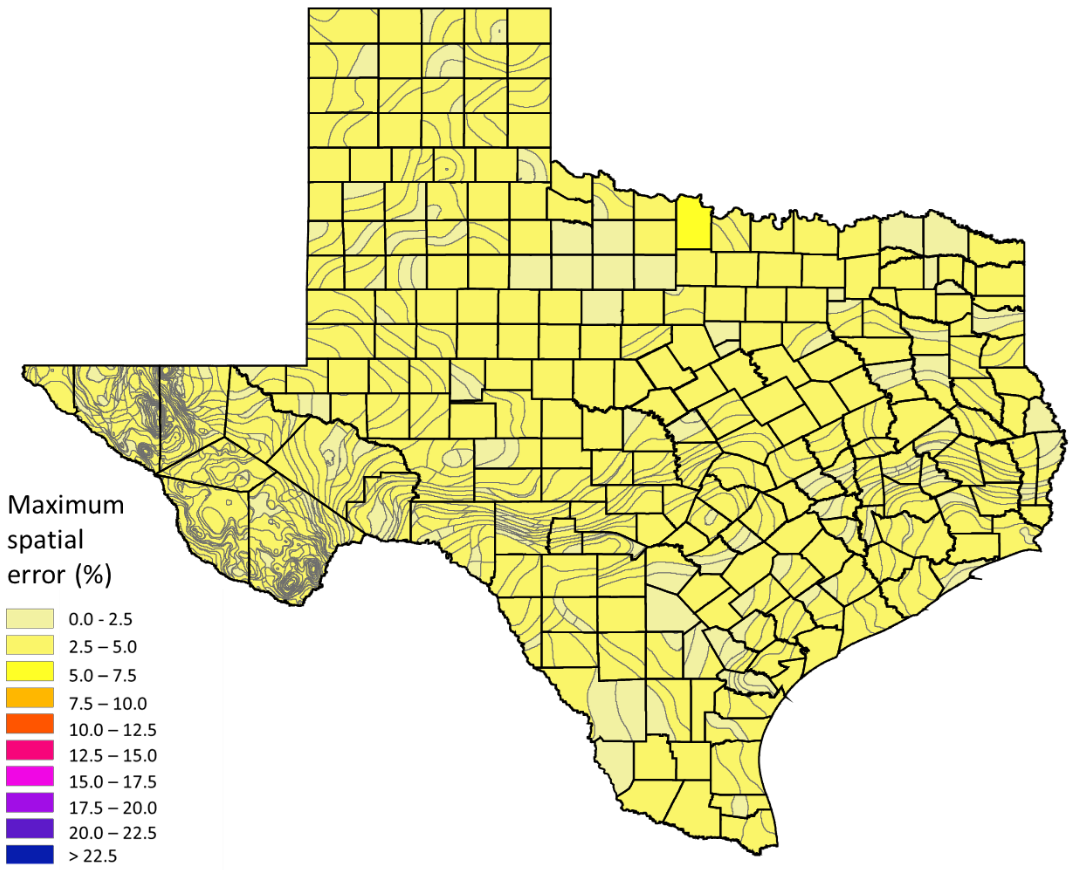


Figure 18. Counties with Error Rates Greater than 10 Percent (N=30).

DELINEATING SUBCOUNTY RAINFALL ZONES

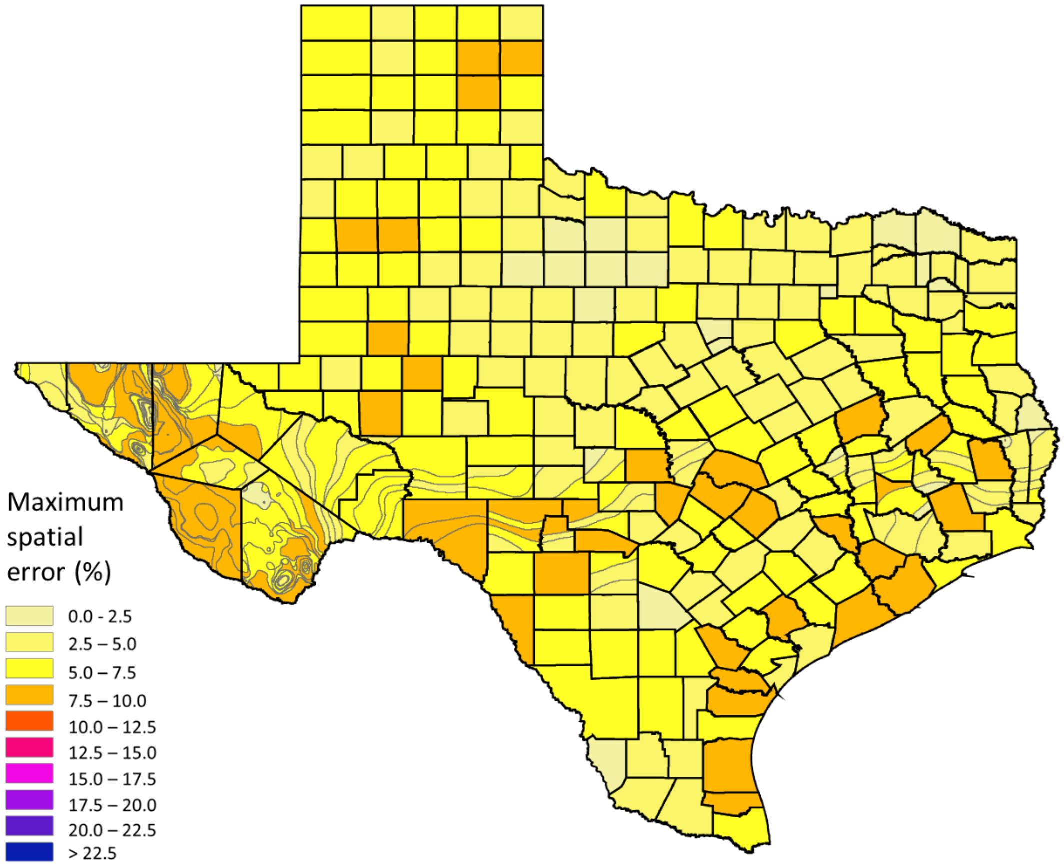
TTI researchers developed an algorithm to split each county into one or more subregions based on achieving a target error rate *and* minimizing the number of subzones within the county. The algorithm recursively splits each county into smaller subzones based on the spatial pattern of rainfall within the county boundary. Specifically, for a single county, each iteration of the algorithm calculates the spatial errors for each storm duration and frequency, and then the maximum spatial error. If the maximum spatial error is greater than a target error (specified at the start of the algorithm), the region is subdivided based on the spatial pattern of rainfall intensity for the storm duration and frequency pair with the highest spatial error. The subdivision method finds an isohyet in the spatial rainfall pattern that *minimizes* the spatial error in the two new zones. This process continues iteratively until the zones produced by each subdivision have a maximum spatial error less than the specified target rate. The algorithm then stores the new rainfall zones in an output file and moves on to the next county.

The two key inputs to the algorithm are the subset of frequency and duration used in an analysis, and the target maximum spatial error. TTI researchers used the same set of storm duration and frequency grids used in the county spatial error analysis. Figure 19 through Figure 23 illustrate the results of the algorithm using error rates of 5, 10, 15, 20, and 25 percent. To aid comparison, each map is drawn using the same color scale to represent spatial error. Table 5 shows the number of subcounty zones generated for each analysis.



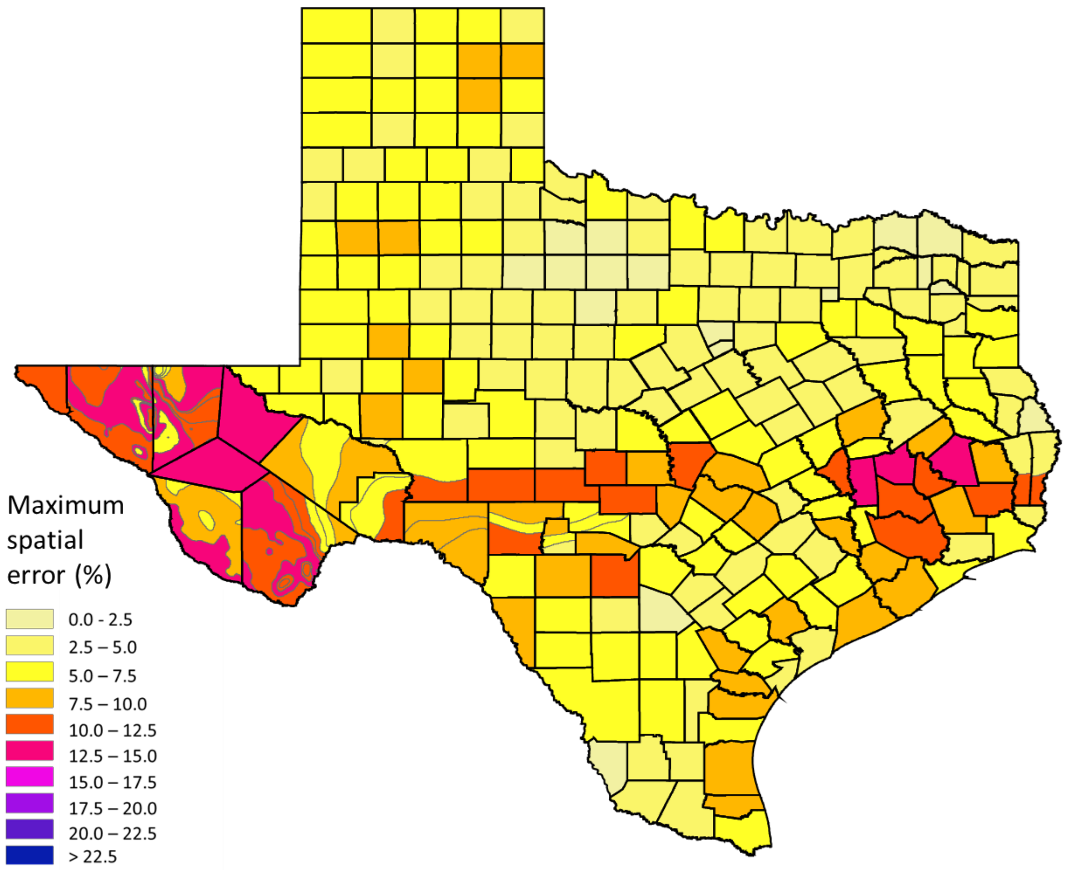
Note: The filled colors show the maximum spatial error in each zone. Each county is outlined with a bold line. Within-county zones are outlined in gray.

Figure 19. Results of County Subdivision Algorithm Run with Target Spatial Error of 5 Percent.



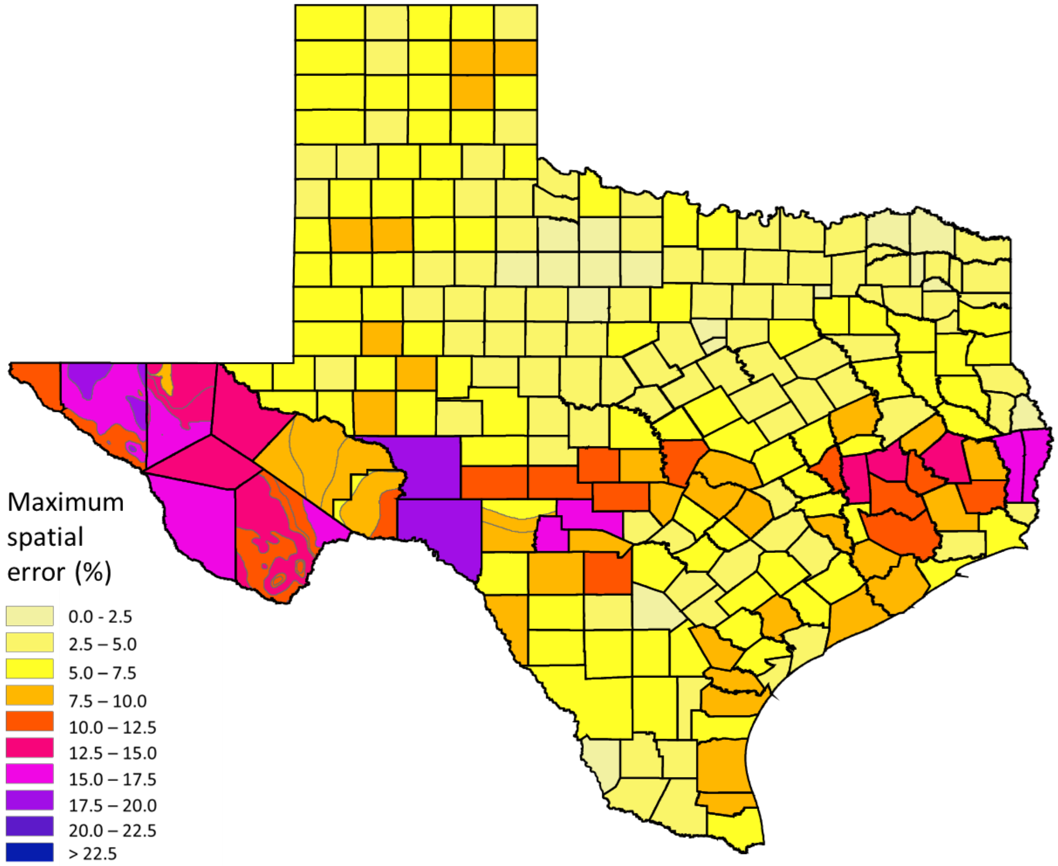
Note: The filled colors show the maximum spatial error in each zone. Each county is outlined with a bold line. Within-county zones are outlined in gray.

Figure 20. Results of County Subdivision Algorithm Run with Target Spatial Error of 10 Percent.



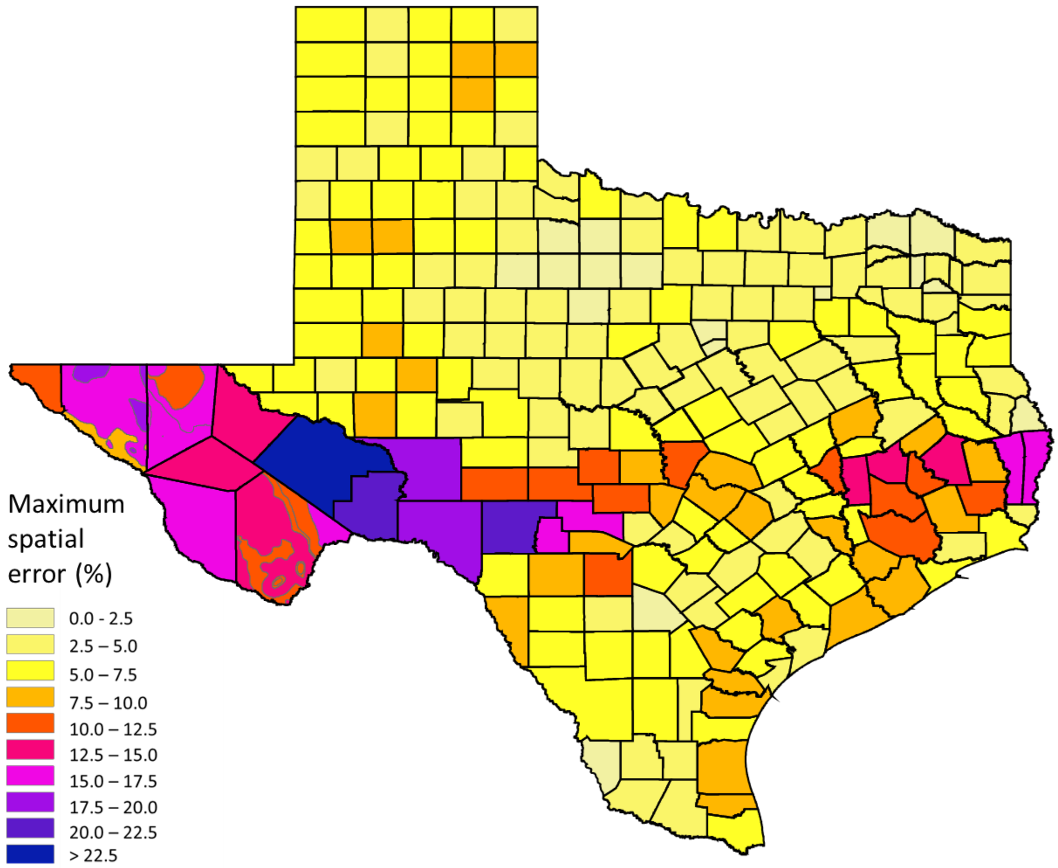
Note: The filled colors show the maximum spatial error in each zone. Each county is outlined with a bold line. Within-county zones are outlined in gray.

Figure 21. Results of County Subdivision Algorithm Run with Target Spatial Error of 15 Percent.



Note: The filled colors show the maximum spatial error in each zone. Each county is outlined with a bold line. Within-county zones are outlined in gray.

Figure 22. Results of County Subdivision Algorithm Run with Target Spatial Error of 20 Percent.



Note: The filled colors show the maximum spatial error in each zone. Each county is outlined with a bold line. Within-county zones are outlined in gray.

Figure 23. Results of County Subdivision Algorithm Run with Target Spatial Error of 25 Percent.

Table 5. Number of Zones Generated Using the County Division Algorithm Using a Variety of Target Maximum Spatial Errors.

Target Maximum Spatial Error	Maximum Number of Zones in a County	Total Number of Zones Statewide
5%	181	1486
10%	47	468
15%	14	312
20%	7	277
25%	7	267

SUMMARY

This chapter explores the spatial error associated with using county boundaries as Texas rainfall zones versus subdividing these counties into smaller zones based on the underlying spatial patterns of rainfall. The current TxDOT hydraulic design guidance is based on *ebd* values derived for each of the 254 Texas counties. This analysis of the Atlas 14 data suggests that 222 out of the 254 counties have spatial error rates less than 10 percent without them being further subdivided. In other words, for these counties, the mean rainfall intensity is within 10 percent of all other values in the county for the subset of storm frequencies and durations used in the analysis. The remaining 30 counties have maximum spatial error rates greater than 10 percent. Many of the counties with higher maximum spatial error occur in west Texas, areas with greater elevation changes than other areas of the state, or southeast Texas within rainfall gradients caused by the Gulf of Mexico.

In the second part of the analysis, an algorithm was used to divide counties into subcounty zones that achieve a specified maximum spatial error. The algorithm divides counties into zones based on the underlying rainfall patterns (provided by Atlas 14). The subdivisions are designed to achieve the target maximum spatial error while minimizing the number of subdivisions. Using this algorithm, 1486 zones are required to achieve a maximum spatial error of less than or equal to 5 percent for every Texas county. A target spatial error of 10 or 15 percent provides a reasonable trade-off between the number of zones and the spatial accuracy of *ebd* predictions.

CHAPTER 7. IMPLEMENTING NEW RAINFALL ZONES AND DEVELOPING NEW HYDRAULIC DESIGN TOOLS

INTRODUCTION

This chapter describes the development of new TxDOT IDF-based hydraulic design tools based on the new NOAA Atlas 14 data. These tools are updates to the current tools and methods used in Texas, notably EBDLKUP-2015v2.1, used to predict rainfall intensities for a specified county, storm duration (t_c), and storm frequency. The *ebd* parameters currently used by TxDOT (and included in the EBDLKUP-2015v2.1 tool) were derived from USGS Scientific Investigations Report 2004-5041, titled *Atlas of Depth-Duration Frequency of Precipitation Annual Maxima for Texas* (Asquith and Roussel 2004). The rationale for using Atlas 14 data to update the TxDOT IDF hydraulic design tools is as follows:

- The Atlas 14 data predict differences in the spatial and temporal patterns of rainfall across the state compared to previous DDF studies.
- Atlas 14 data are available at higher spatial resolution than previous studies. This provides an opportunity for TxDOT to increase the spatial accuracy of its design tools.
- Atlas 14 data provide estimates of DDF data derived from AMS and PDS, and for a greater range of storm durations and frequencies than previous DDF studies.

Previous chapters of this report have independently investigated the implications of these changes to the TxDOT hydraulic design process. Chapter 5 describes differences in rainfall intensities reported by the new Atlas 14 data versus the values currently being predicted by the current TxDOT *ebd* coefficients. Chapter 6 explores methods and the rationale for dividing rainfall zones into subcounty zones. This chapter describes the development of new TxDOT hydraulic design tools, based on the research and conclusions described in previous chapters.

DEFINING AND IMPLEMENTING TEXAS RAINFALL ZONES

TTI researchers used the maps and information created in Chapter 6 and outreach to county hydraulic engineers and other stakeholders to finalize a statewide map of Atlas 14–derived rainfall zones to be used by TxDOT. The statewide map was chosen to achieve a balance of improving the spatial accuracy of IDF predictions without creating an unnecessarily large number of rainfall zones.

Statewide Approach

TTI researchers created a unified set of Texas rainfall zones, based on consistent statewide methods outlined in Chapter 6. TTI researchers decided on a target spatial error of 20 percent for three counties (Brewster, Hudspeth, and Culberson), 15 percent for eight counties (Presidio, Jeff Davis, Pecos, Edwards, Terrell, Val Verde, Reeves, and Crockett), and 10 percent for the remainder of the counties. The target maximum spatial error was increased for counties in west Texas because a 10 percent maximum spatial error resulted in a large number of subcounty zones, which could not be easily incorporated into the hydraulic design process. Figure 24 shows the rainfall zones obtained from this statewide delineation process.

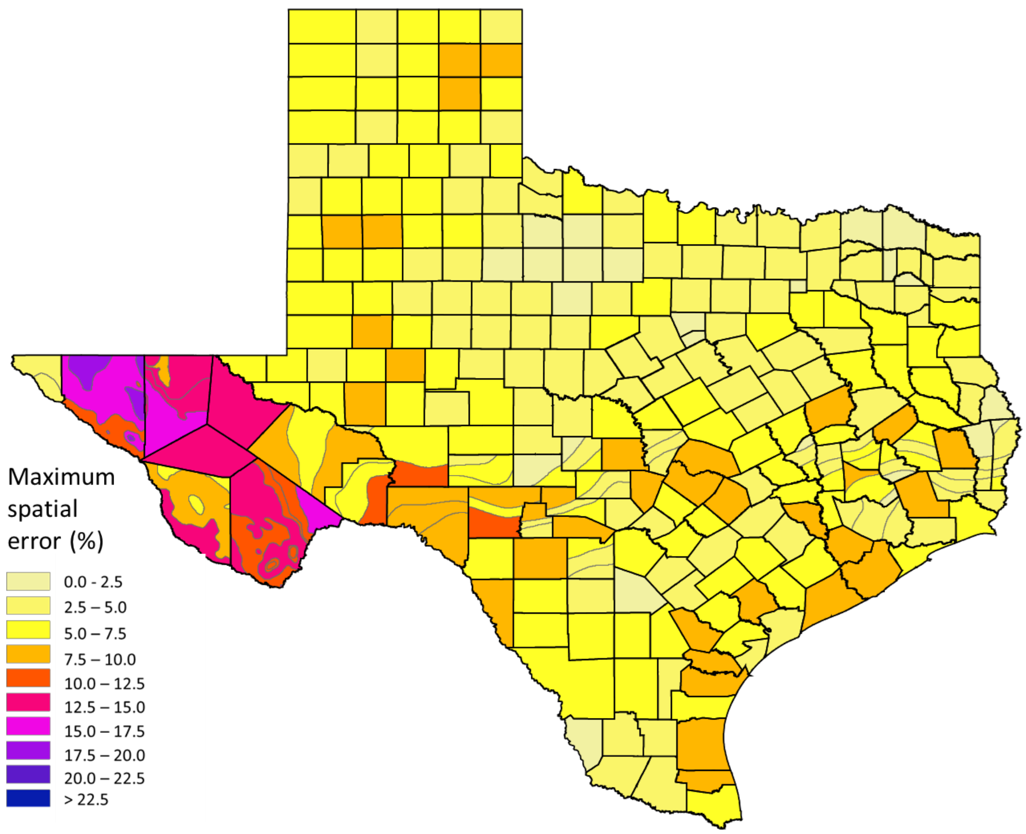


Figure 24. Rainfall Zones Defined Using the Statewide Method.

Custom County Zones

To supplement the statewide approach, other county or regional stakeholders were asked if they were using or planning to use their own Atlas 14–based rainfall zones within their county or other jurisdictions. In some cases, these custom zones extended beyond county level boundaries. In these cases, the custom zones were clipped to the relevant county boundary. Three organizations responded with preferred or custom rainfall zones:

- City of San Antonio (Bexar County). Figure 25 shows a map of Bexar County's preferred IDF zones, and Table 6 shows the spatial errors.
- Harris County Flood Control District. Figure 26 shows a map of Harris County's preferred DDF zones that they intend to use for larger scale hydraulic design (watershed scale). Table 7 shows the spatial errors associated with these three zones. For IDF work, Harris County has decided to use a conservative approach in which rainfall intensity estimates for Zone 3 are used throughout Harris County (Zone 3 yields the highest rainfall intensities compared to the remaining two zones).
- Williamson County. Figure 27 shows a map of Williamson County's preferred IDF zones, and Table 8 shows the spatial errors.

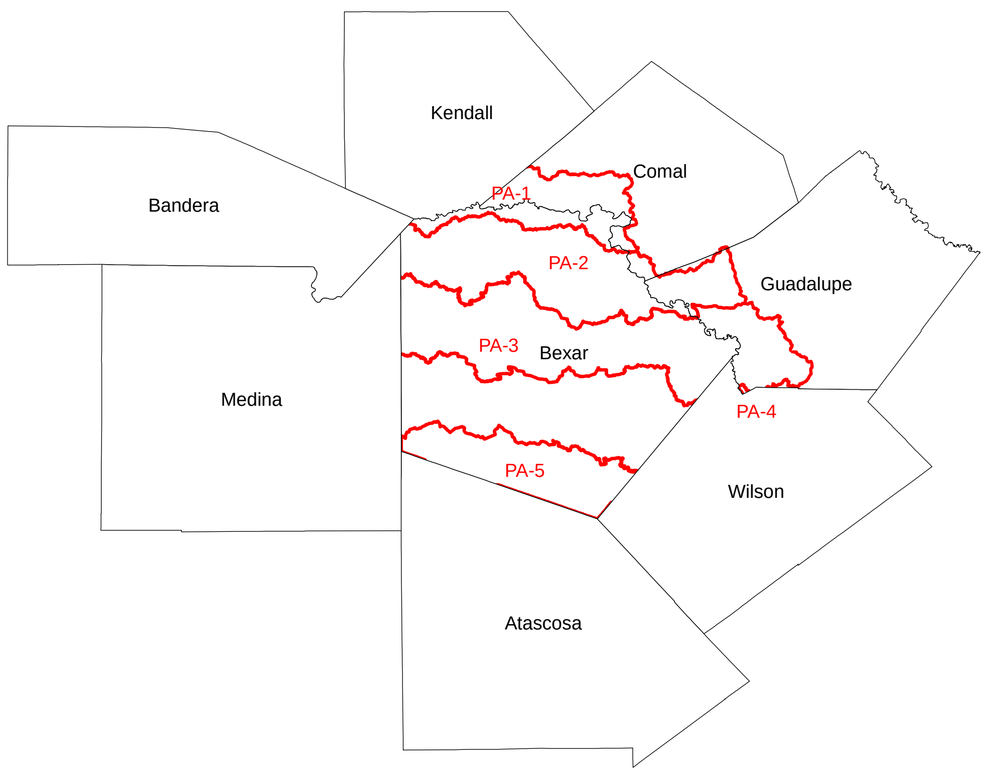
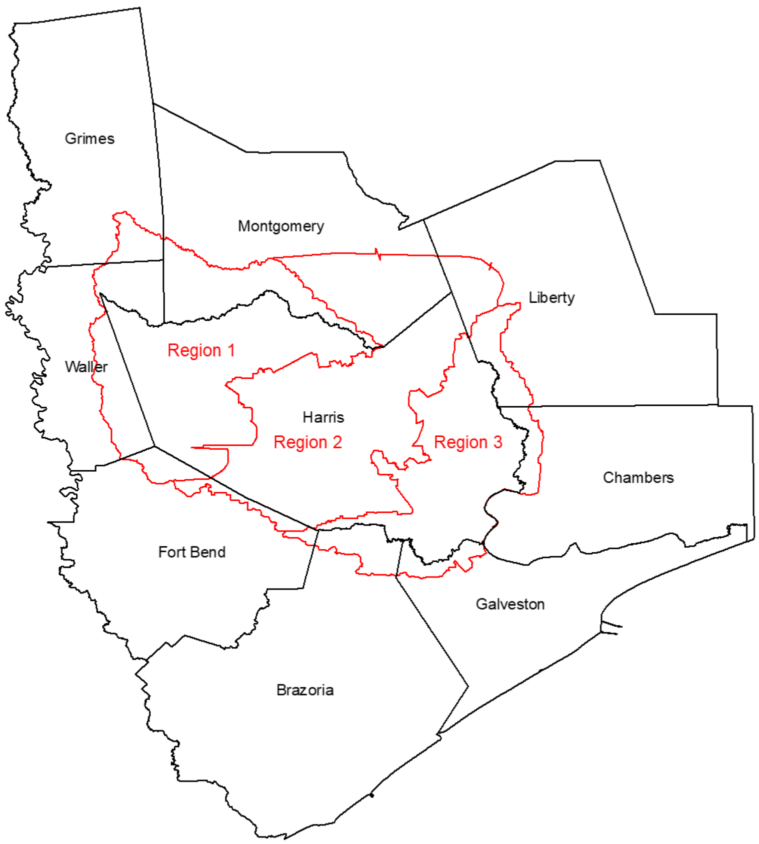


Figure 25. Custom IDF Rainfall Zones Defined by Bexar County.

Table 6. Maximum Spatial Error Evaluated for Bexar County Custom IDF Rainfall Zones.

Rainfall Zone	Maximum Spatial Error (Percent)
PA-1	0.93
PA-2	2.99
PA-3	3.47
PA-4	2.64
PA-5	1.65



Note: These rainfall zones were originally created for DDF design. For IDF work, the Harris County authorities recommend using the IDF data for Region 3 for the entire area.

Figure 26. Custom IDF Rainfall Zones Defined by Harris County.

Table 7. Maximum Spatial Error Evaluated for Harris County Custom IDF Rainfall Zones.

Rainfall Zone	Maximum Spatial Error (Percent)
Region-1	7.30
Region-2	7.02
Region-3	5.98
Region 3 applied to entire Harris County	11.61

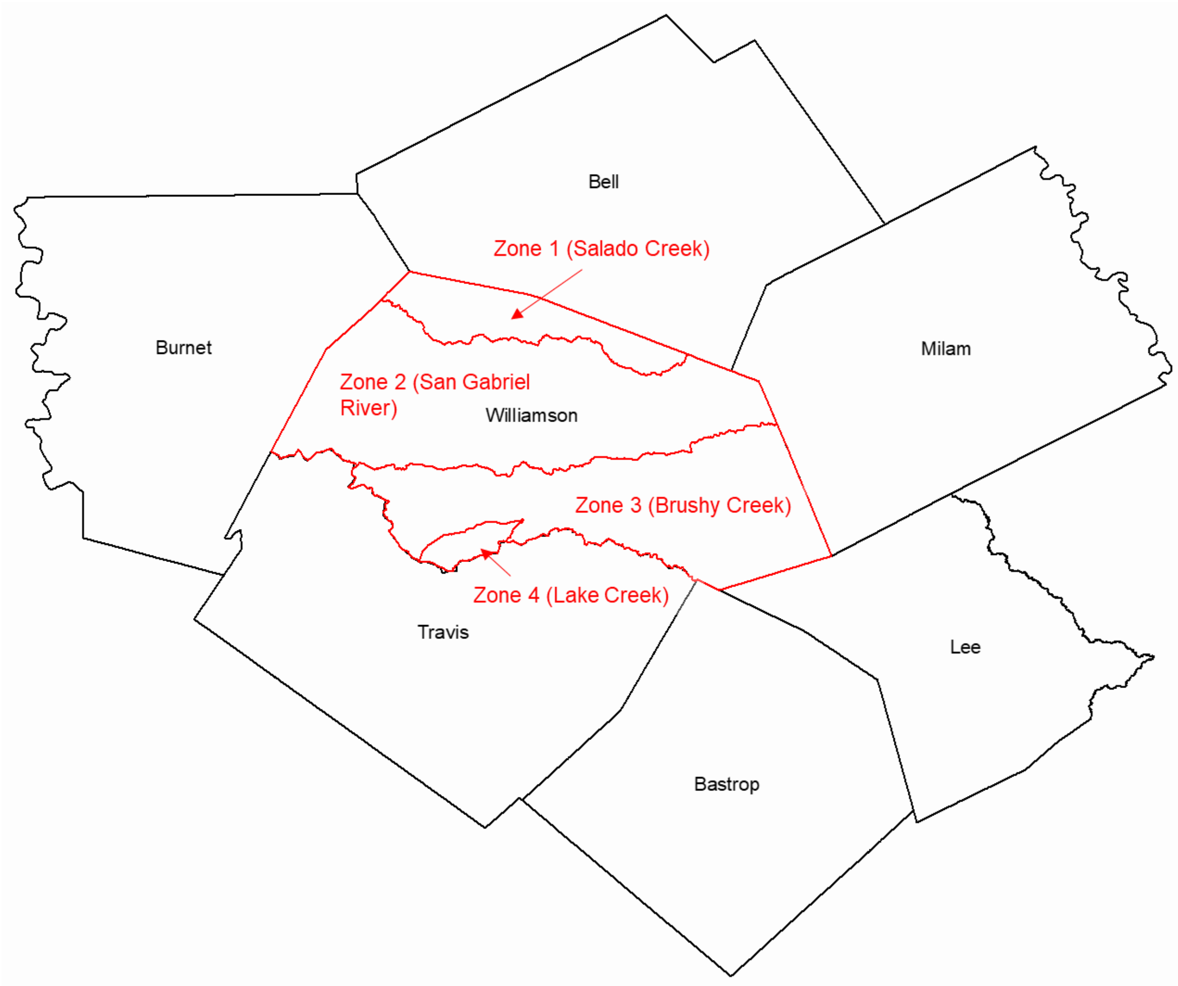


Figure 27. Custom IDF Rainfall Zones Defined by Williamson County.

Table 8. Maximum Spatial Error Evaluated for Williamson County Custom IDF Rainfall Zones.

Rainfall Zone	Maximum Spatial Error (Percent)
Zone-1	2.43
Zone-2	5.55
Zone-3	8.38
Zone-4	1.96

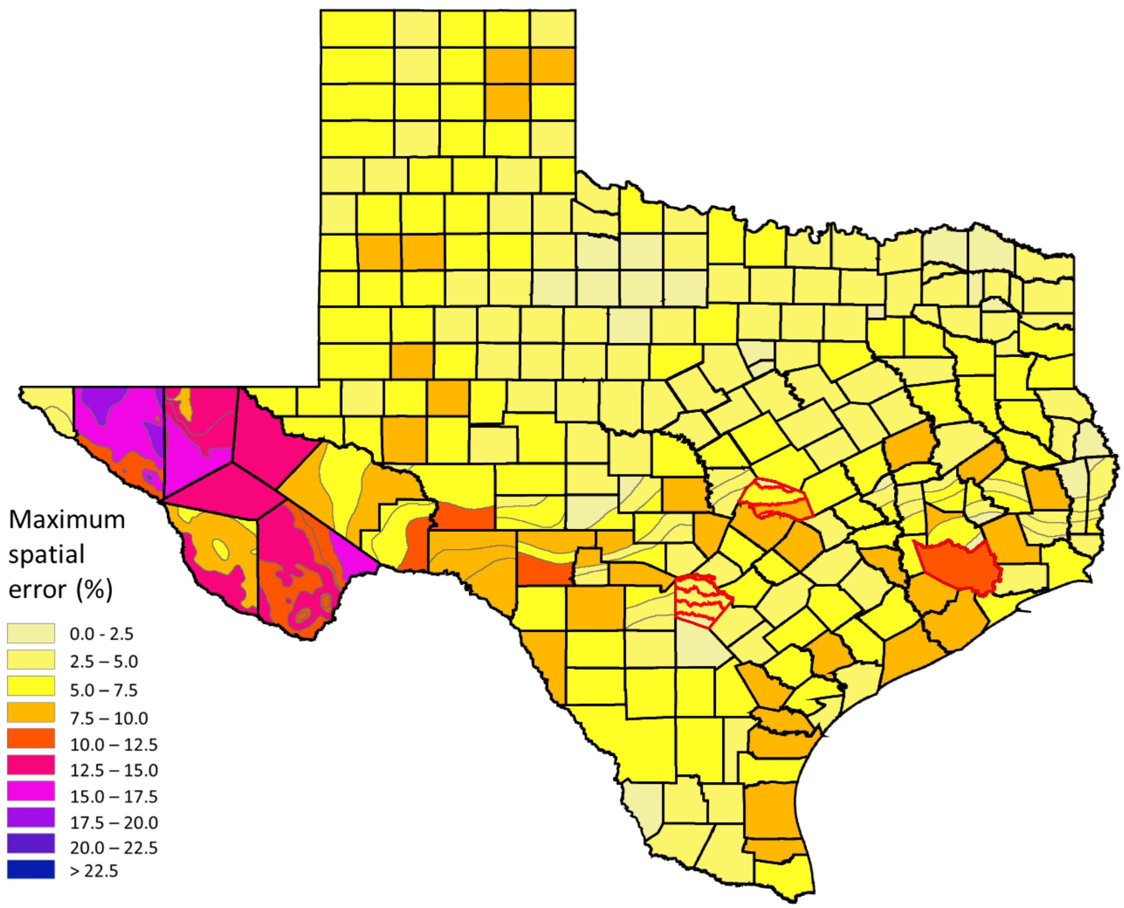
Final Statewide Rainfall Zones

To create the final statewide map of IDF rainfall zones, the custom IDF rainfall zones provided by counties were overlaid onto the zones created using the statewide method. Where custom zones overlapped surrounding counties (Harris and Bexar Counties), the custom zones were clipped by the surrounding county boundaries. Table 9 provides a summary of the criteria used to develop the final statewide IDF rainfall zones. Figure 28 shows the finalized Texas IDF rainfall zones.

The methods outlined in Chapter 4 were then used to estimate *ebd* coefficients for each rainfall zone, using both PDS and AMS Atlas 14 data.

Table 9. Summary of Criterion for Defining the Finalized Texas IDF Rainfall Zones.

Target Error (Percent)	Counties
20	Brewster, Hudspeth, and Culberson
15	Presidio, Jeff Davis, Pecos, Edwards, Terrell, Val Verde, Reeves, and Crockett
10	All other counties
Custom	Bexar, Williamson, and Harris (Zone 3 applied to entire county)



Note: Custom IDF zones are outlined in red.

Figure 28. Final Texas Rainfall Zones Incorporating Custom IDF Zones from County Stakeholders.

UPDATING THE EBDLKUP TOOL

TTI researchers used the new Texas rainfall zones and corresponding *ebd* coefficients to update TxDOT's existing Excel-based *ebd* look-up tool. The current tool is called EBDLKUP-2015v2.1. The provisional name of the updated tool is EBDLKUP-2019. Figure 29 shows a screenshot of the current EBDLKUP-2015v2.1 for predicting rainfall intensity for a specified Texas county and t_c. The user specifies the t_c, units, and county of interest. Using this information, the spreadsheet provides storm intensity estimates (between 50 percent and 1 percent storm frequencies at a county level) for six selected durations and storm frequencies between 2 and 100 years for the selected county.

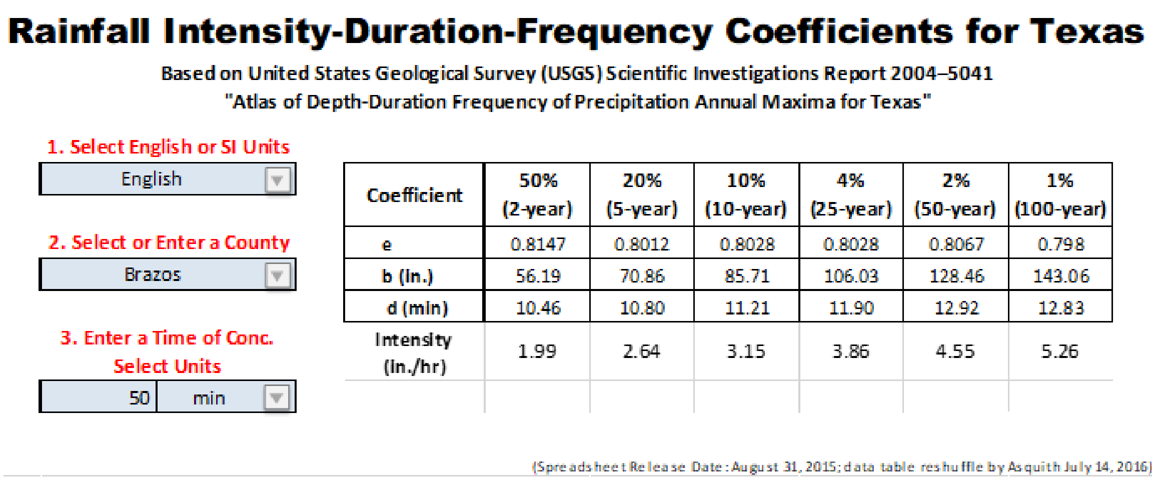


Figure 29. Screenshot of the EBDLKUP-2015v2.1.xls Tool.

The new EBDLKUP-2019 tool is designed to provide a similar user experience to EBDLKUP-2015v2.1. The major differences between the new and current tools are as follows:

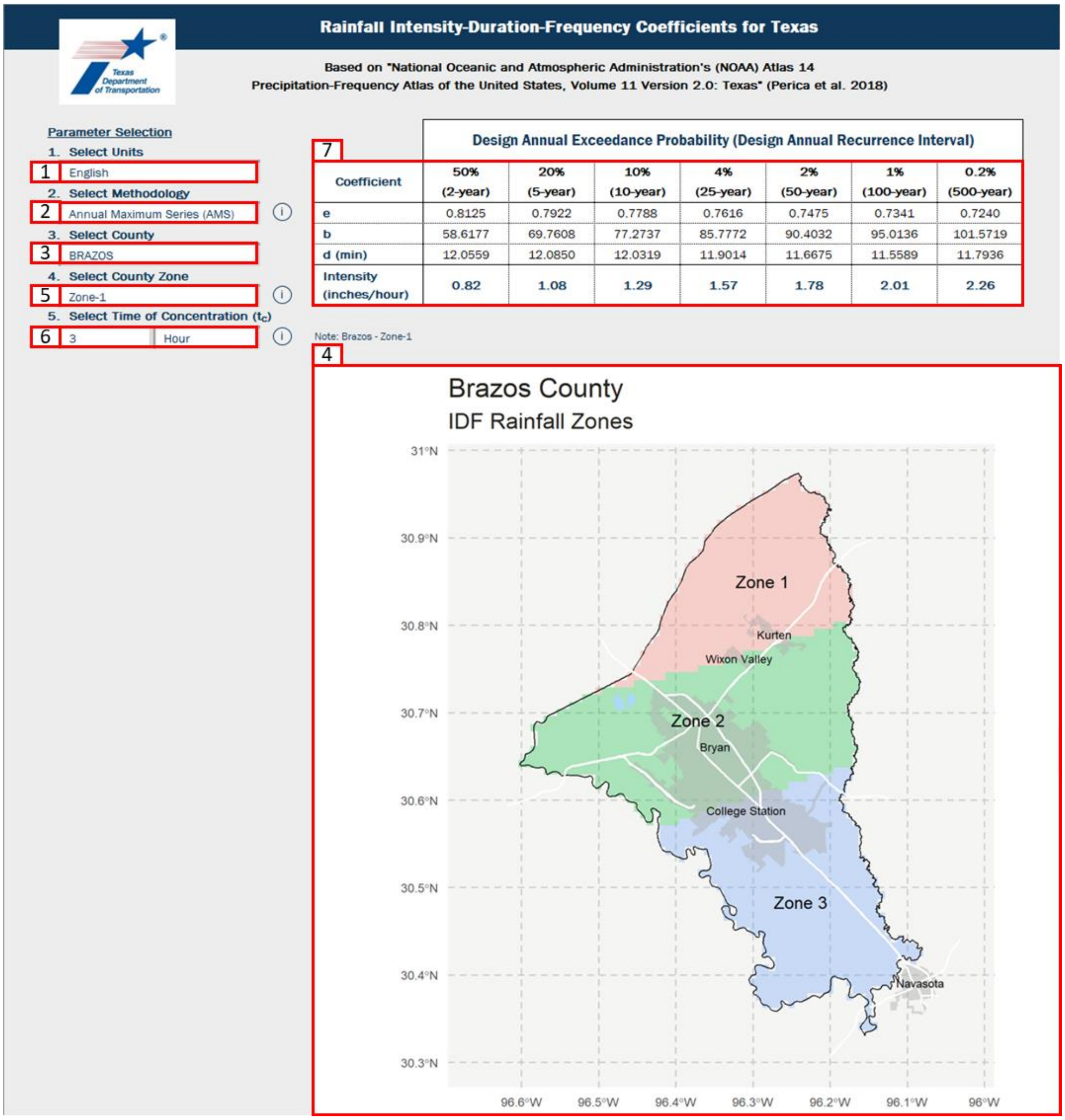
- All *ebd* coefficients contained within EBDLKUP-2019 have been updated to values derived from the Atlas 14 data.
- EBDLKUP-2019 incorporates subcounty rainfall zones for a number of counties (approximately 30). Following the design of EBDLKUP-2015v2.1, the county is still the primary method of determining the location of a project. However, in the new EBDLKUP-2019 tool, the user is prompted to enter a subcounty rainfall zone using an additional drop-down control. To help users make an appropriate selection, the tool provides county-specific maps detailing all rainfall zones within a selected county.

- An option has been added enabling users to select *ebd* coefficients derived from AMS or PDS.
- The new EBDLKUP-2019 tool provides rainfall intensity predictions for up to 500-year return frequencies (compared to 100-year frequencies in EBDLKUP-2015v2.1).

EBDLKUP-2019 User Interface

Figure 30 shows an annotated screenshot of the EBDLKUP-2019 user interface. The annotations are numbered in the order of the selections required by a user to obtain rainfall intensity predictions:

1. The user selects English or metric units for the prediction.
2. The user selects whether the rainfall intensity predictions should be based on *ebd* values obtained from Atlas 14 AMS or PDS data.
3. The user selects the county in which the hydraulic project is located.
4. The county selection uploads a map that shows one or more rainfall zones within the county. The maps help the user determine the zone-specific location of the project.
5. The county selection populates the "County Zone" drop-down box with all valid zones in the county. The user selects the appropriate county zone using the map or using an accompanying Google Earth Keyhole Markup Language (KML) file (described in the next section).
6. The user selects the t_c, with appropriate time units (minutes or hours).
7. Any changes to the selection boxes described previously result in updates to the summary table of rainfall predictions. The summary table provides the predicted rainfall intensity for the selected inputs and for the seven design storm frequencies (2, 5, 10, 25, 50, 100, and 500 year). The summary table also shows the *ebd* coefficients used in the prediction.



Coefficient	Design Annual Exceedance Probability (Design Annual Recurrence Interval)						
	50% (2-year)	20% (5-year)	10% (10-year)	4% (25-year)	2% (50-year)	1% (100-year)	0.2% (500-year)
e	0.8125	0.7922	0.7788	0.7616	0.7475	0.7341	0.7240
b	58.6177	69.7608	77.2737	85.7772	90.4032	95.0136	101.5719
d (min)	12.0559	12.0850	12.0319	11.9014	11.6675	11.5589	11.7936
Intensity (inches/hour)	0.82	1.08	1.29	1.57	1.78	2.01	2.26

Figure 30. Annotated Screenshot of the New EBDLKUP-2019 Tool.

The inputs and formulas in the workbook include error checks to prevent selection or calculation errors. The worksheet has been paginated to print on an 8.5 × 11-inch sheet of paper in portrait mode to assist in project documentation. The printout includes a footer with the date, tool name, and version number. As in EBDLKUP-2015v2.1, the *ebd* coefficients used in the predictions are contained within hidden worksheets. Additionally, all cells in the worksheet, except those used in entering selection, are locked for editing.

County Maps

The new EBDLKUP-2019 tool has increased the spatial resolution of *ebd* coefficients from county-level to subcounty rainfall zones. To assist the user to quickly identify an appropriate rainfall zone, TTI researchers embedded 254 county maps into the tool. Each map shows the rainfall zones for each county and also provides lines of latitude and longitude, major roads, urban areas, and waterbodies useful as reference points.

Google Earth KML FILE

In addition to the county maps embedded in the EBDLKUP-2019 tool, TTI researchers developed a Google Earth KML file that can be used to locate rainfall zones relevant to a project location. Figure 31 provides a screenshot of the KML file loaded into Google Earth. The dialog box appears when a user clicks within any zone on the map and displays the county name and rainfall zone.

Note: The dialog displays the name of the county and county rainfall zone.

Figure 31. Screenshot of Google Earth KML File That Can Be Used to Look Up the Appropriate Rainfall Zone for a Project.

CHAPTER 8. CONCLUSION

This technical report describes research to incorporate newly available NOAA Atlas 14 DDF data into TxDOT's statewide hydraulic design methods for small watersheds. The project has led to the development of EBDLKUP-2019, a new tool that hydraulic engineers can use to accurately predict rainfall intensities at any location within Texas. This tool updates an existing tool (EBDLKUP-2015v2.1) by incorporating new *ebd* coefficients derived from latest available DDF data provided by Atlas 14. The new, updated tool also improves on the spatial accuracy of predictions provided by EBDLKUP-2015v2.1.

Much of the research undertaken during this project involved analyses designed to investigate how the Atlas 14 data could be used to improve the spatial accuracy of rainfall intensity predictions. Chapter 5 of this report illustrates that Atlas 14 reports differences in the spatial pattern of rainfall DDF (and hence IDF) compared to previous studies. This is the primary reason why the current *ebd* coefficients and EBDLKUP tool should be updated. These differences in rainfall pattern, which are the result of improved data, should be accounted for in the current tools and procedures used in TxDOT hydraulic design. The largest differences in rainfall intensity occur in the southeast Texas and central Texas, and for storm durations greater than 12 hours (24-hour durations are shown in Figure 10). In these locations, and for storms of these durations, rainfall intensity predictions made using TxDOT's current *ebd* coefficients may be 50 percent lower than those predicted using the new Atlas 14 derived coefficients.

Chapter 6 of this report analyses the spatial accuracy of using county-level rainfall zones and investigates how county rainfall zones could be subdivided based on underlying patterns of rainfall and a predetermined spatial error rate. The methodology was designed to improve the spatial accuracy of predictions, while ensuring the TxDOT design process remains practically useful. The method is a quantitative, objective approach to creating rainfall zones. It has the advantage of a repeatable methodology that can be explained and rationalized to other stakeholders.

However, this objective methodology was also supplemented by more subjective, practical considerations. TTI researchers originally set out to ensure all counties were represented by one or more rainfall zones that resulted in less than 10 percent spatial error in prediction. In other words, the representative *ebd* values for a rainfall zone are within 10 percent of the fully spatially explicit estimates provided by Atlas 14 (resolution of 0.008 decimal degrees). However for a number of west Texas counties, this error rate was not practically achievable because a 10 percent error rate results in a large number of distinct zones, which would complicate the hydraulic design process. In these regions, researchers used a higher target error rate (between 15 and 25 percent). Additionally, for three counties (Harris, Williamson, and Bexar), rainfall zones were determined by local agencies, so that they were consistent with their local practices.

The research into rainfall zone delineation was undertaken in parallel with the development of updates to TxDOT's hydraulic design tool—EBDLKUP-2015v2. The major challenge for this research was to ensure that, if counties were subdivided, engineers would be able to successfully georeference their projects relative to these subcounty zones, and therefore be able to obtain an accurate rainfall intensity prediction. The major information technology challenge was to maintain the existing spreadsheet based approach for delivering this information to hydraulic engineers. Researchers developed a solution that uses 254 county rainfall zone maps that are permanently embedded into the spreadsheet. These sketch maps can be used to roughly determine rainfall zones in most design cases, especially in counties with few zones, or whenever projects can easily be located on the maps relative to zone boundaries or other simple features such as roads. For projects that are closer to the border of rainfall zones, or otherwise more difficult to locate, TTI researchers developed a Google Earth KML file to accompany the Excel workbook. The KML file shows the rainfall zones in the Google Earth search and map interface, and enables project locations to be determined efficiently and accurately. Overall, TTI researchers have demonstrated that new, subcounty rainfall zones can be introduced into the provisional EBDLKUP-2019 tool without affecting the simplicity of the existing hydraulic design process.

FUTURE WORK AND RECOMMENDATIONS

TTI researchers suggest the following opportunities for future work on Texas Rainfall Coefficients and tools for predicting rainfall intensity:

1) The current Excel based tool could be replaced with a web-based interface. A spatial, web-based interface that incorporates dynamic maps would allow design engineers to rapidly locate a project relative to rainfall zones and deliver accurate rainfall intensities. The web-based approach would also have the benefit of providing a single, centralized tool.

Currently, the spreadsheet tool is necessarily distributed among a large number of computers. This makes it difficult to update or recall the tool. In contrast, a web-based tool resides on a single server (controlled by TxDOT), which would ensure updates to either the parameters, calculations or user interface are universally adopted by users of the tool. A web-based tool (or suites of tools) could also be useful for cataloguing or inventorying all hydraulic design structures in the state (including their design standards). Such an inventory would enable meta-analyses capable of informing current and future design guidance.

2) During this project, the TxDOT project team contacted county hydraulic design engineers to ask if they have custom defined IDF rainfall zones for their jurisdictions. All three of the custom zones developed by county engineers (Bexar, Harris, Williamson) are based on watershed boundaries or hydraulic units, such as those delineated by USGS. These hydraulic units are probably used because of their relevance to larger scale hydraulic design (such as flood plain analysis). In many respects, it makes sense to maintain a consistent set of rainfall prediction zones for both small and large scale hydraulic design. TTI researchers suggest that the current rainfall zone delineation algorithms could be modified to derive efficient rainfall zones based on aggregations of official hydraulic units (such as those provided by the United States Geological Survey). It would be possible to use the same concepts of spatial error to join hydraulic units together to achieve a specified level of spatial accuracy.
3) The current TxDOT approach for predicting rainfall intensity is to use representative rainfall zones. However, the Atlas 14 data are provided at a spatial resolution of 0.008 decimal degrees. A web-based approach would *potentially* enable TxDOT to abandon the concept of representative rainfall zones, and instead deliver rainfall intensity predictions at the maximum resolution of the Atlas 14 data (or subsequent DDF studies). One of the advantages of the rainfall zone based approach is the ease with which predictions can be validated, audited, and otherwise quality assured within the design process. A web-based, point estimate approach would require this quality assurance to be re thought. However, rather than trying to validate a static database of previously derived *ebd* coefficients, quality assurance could be maintained by validating algorithms that dynamically derive the *ebd* coefficients from the raw atlas data. Other quality assurance might involve engineers plotting the location of projects and retaining copies of calculations. Although the technology exists to provide fine scale rainfall intensity predictions, TTI researchers suggest

that any changes to the underlying concept of using rainfall zones should be well researched before implementation.

4) The Atlas 14 data indicate a significant shift in statewide rainfall patterns relative to previous studies. This means that there are areas of the state for which hydraulic engineers may be over designed (more protective than current guidance), but more seriously, areas that are under designed (less protective than current guidance). The potential consequence of under designed structures is increased flooding, and associated effects on property, traveler safety and mobility and transportation infrastructure. Chapter 5 of this report provides maps that could be used to determine areas with under designed hydraulic structures. The Atlas 14 data and historic *ebd* coefficients provide valuable information for more detailed studies on the current design standards of hydraulic infrastructure given changes in the latest available data on rainfall patterns.

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APPENDIX – VALUE OF RESEARCH

INTRODUCTION

TxDOT hydraulic design engineers use the rational method to design cost effective hydraulic structures for watersheds less than 200 acres in size. The rational method uses the following formula to estimate runoff following a rainfall event:

$$Q = CIA \qquad \text{Equation A-1}$$

Where:

- Q is the maximum rate of runoff.
- C is a runoff coefficient that determines the proportion of rainfall that translates to runoff.
- A is the size of the drainage area.
- I is rainfall intensity.

The rational method provides a simple way of estimating runoff during a rainfall event. This project deals with providing tools to estimate rainfall intensities (I in Equation A-1) for use in the rational method.

Engineers design hydraulic structures to handle runoff associated with a design storm. A design storm is defined by the duration and intensity of a storm and by the frequency with which a given storm occurs in the climate record. Storm frequency is often expressed using Average Return Interval (ARI) or Annual Expected Probability (AEP). ARI is defined as the expected time between storms of a given rainfall intensity, while (ARI) or the probability that a given rainfall intensity will be exceeded in any year.

In hydraulic design, an engineer first selects an AEP or ARI for the project of interest. For example, an AEP of 1 in 100 (or 1 percent) means that the structure is intended to handle runoff generated by a storm that is expected to occur only one year out of one hundred.

Once an AEP or ARI is selected, the engineer determines the minimum length of time required for peak flow to occur at the watershed outlet. This time period is termed the t_c and is an estimate of the minimum time required for surface water to flow from the hydrologically most distant parts of the watershed to its outflow.

The rainfall intensity for the design storm, defined by AEP (or ARI) and storm duration t_c, is entered into the rational method equation to predict peak surface runoff. Assuming variables C and A (from Equation A-1) are known, a simplified summary of the hydraulic design process is as follows:

1. Define a design storm based on the geographic location of a project, storm duration, and the frequency of a storm event.
2. Estimate the rainfall intensity of this design storm (I), and uses the rational method formula (Equation A-1) to predict runoff.
3. Design hydraulic structures to accommodate the runoff predicted for the design storm.

PROJECT GOALS AND OUTCOMES

This project deals with the development of a new tool (and information) that TxDOT engineers can use to estimate the rainfall intensity for a specified design storm at any location in Texas (effectively step 2 of the process above).

The tool is a Microsoft Excel spreadsheet, which contains formulas to estimate rainfall intensity for a specified design storm at any location in Texas (Figure 32).

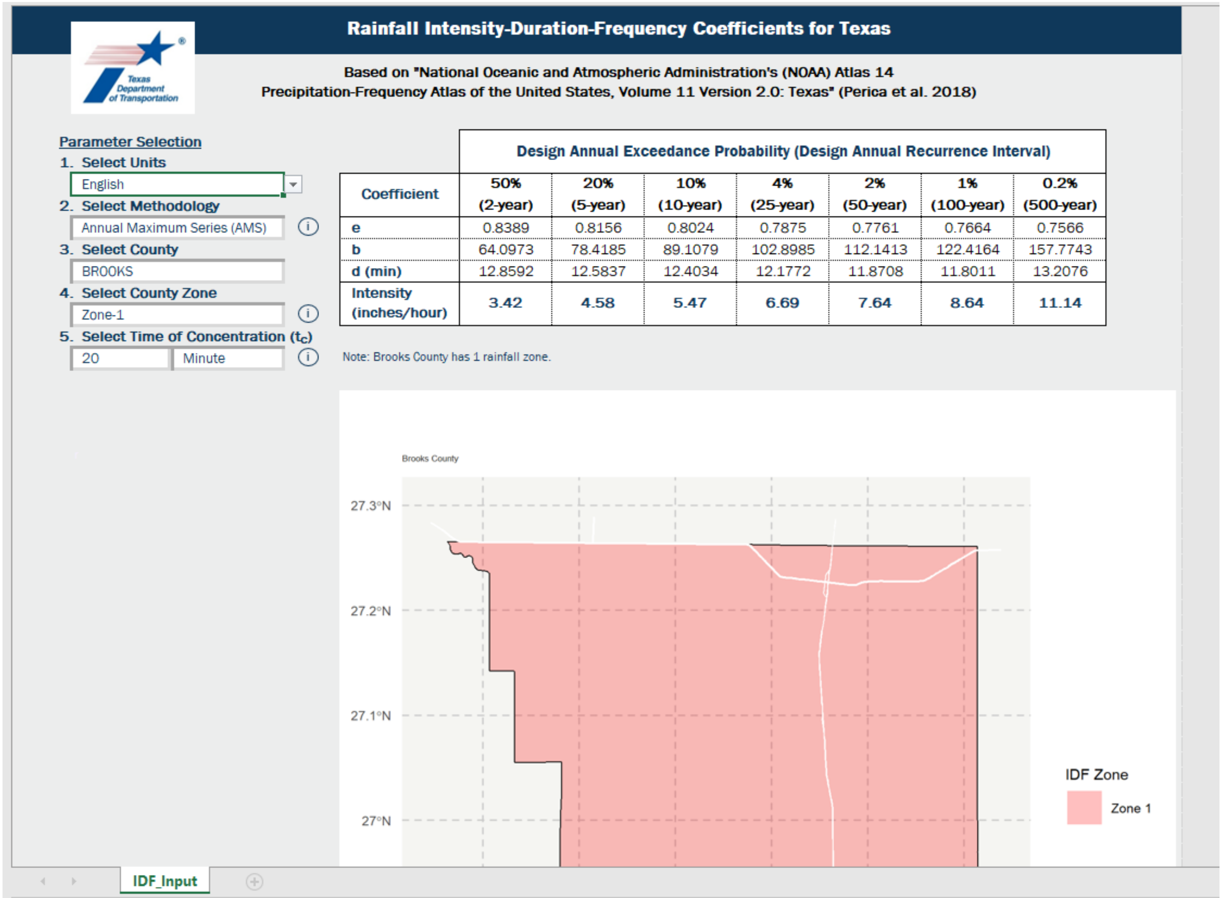

Figure 32. Screenshot of EBDLKUP-2019, a Microsoft Excel Based Tool That Provides Hydraulic Design Engineers with Design Storm Rainfall Intensity Estimates.

The EBDLKUP-2019 tool using the following formula to furnish rainfall intensity estimate:

$$I_{ARI,location} = \frac{b}{(t_c+d)^e} \qquad \text{Equation A-2}$$

Where:

$I_{ARI,\ location}$ is the storm or precipitation intensity for a specified ARI and location.

t_c is the time of concentration or critical duration of the storm.

e, *b*, and *d* are fitted parameters.

The parameters e, b, and d in Equation A-2 are sometimes referred to as the Texas rainfall coefficients and are fitted to historical rainfall data.

A recent National Oceanic and Atmospheric Administration (NOAA) project called Atlas 14 has analyzed 73,860 years of rainfall data in Texas to develop a comprehensive set of maps detailing rainfall intensity for ARIs between 1 and 1000 years (1, 2, 5, 10, 25, 50, 100, 250, 500, and 1000 years) and for fixed storm durations between 5 minutes to 60 days (2, 5, 10, 15, 30, and 60 minutes; 1, 2, 3, 6, 12, and 24 hours; and 2, 3, 4, 7, 10, 20, 30, 45, and 60 days). The Atlas 14 data provide the most up to date, accurate estimates of location specific rainfall intensities for Texas. A core rationale for this research project is to ensure that these new rainfall intensity estimates are incorporated into TxDOT's hydraulic design processes.

In this project, researchers fitted Equation A-2 to the NOAA Atlas 14 data to determine Texas rainfall coefficients that can be used to predict design storm rainfall intensity at any location in Texas. These coefficients were then incorporated into a Microsoft Excel Spreadsheet tool (called EBDLKUP-2019) that will be disseminated to TxDOT engineers to accurately predict design storm rainfall intensity for the purposes of hydraulic design. The new Atlas 14 rainfall coefficients will also be reused in TxDOT's next generation of hydraulic design software (Bentley OpenRoads designer and associated products).

VALUE OF RESEARCH

The value of research benefit factors identified by TxDOT are summarized in Table 10. In the following sections, TTI researchers provide qualitative information on how this project will benefit these categories. Following these qualitative assessments, TTI researchers provide data, information, and assumptions to support a quantitative value of research assessment.

Table 10. Value of Research Benefit Categories Explored in This Report.

Benefit Area	Qualitative	Economic	Both	TxDOT	State	Both
Level of Knowledge	X			X		
Management and Policy	X			X		
Quality of Life	X			X		
Customer Satisfaction	X			X		
System Reliability		X		X		
Increased Service Life		X		X		
Improved Productivity and Work Efficiency		X		X		
Traffic and Congestion Reduction		X			X	
Reduced Construction, Operations, and Maintenance Cost		X			X	
Infrastructure Condition		X				X
Engineering Design Improvement			X			X
Safety			X			X

QUALITATIVE FACTORS

Level of Knowledge

This project builds upon established methods to provide rainfall intensity predictions for the state of Texas. Currently TxDOT uses a similar tool to the one developed in this project (EBDLKUP-2015v2) to estimate design storm rainfall intensities across Texas. The existing tool is based on rainfall data derived from two research studies that were partly funded by TxDOT:

- *Depth Duration Frequency of Texas, a Study* (Asquith 1998).
- *Atlas of Depth-Duration Frequency of Precipitation Annual Maxima for Texas* (Asquith and Roussel 2004).

These studies focused on rainfall within Texas and used methods and data similar to those used by Atlas 14. The new Atlas 14 study includes 73,860 years' worth of Texas rainfall records compared to the 51,370 records used by Asquith (1998). Since 1998, there have been improvements in the technology used to sample rainfall. Atlas 14 uses data from more weather stations that sample rainfall at intervals less than 1 hour compared to previous studies, which will improve subhourly rainfall estimates (8,232 years' worth of records in Atlas 14 compared to 3,030 years in previous study). The Atlas 14 methodology also includes improved methods of spatial interpolation, yielding data at a spatial resolution of approximately half a mile (compared to isohyets produced in previous studies). In short, TTI researchers suggest that the new Atlas 14 data are now the most accurate source of rainfall intensity data that exists for Texas. Incorporating this information into TxDOT's hydraulic design process will generally increase the accuracy of data used in hydraulic designs.

This project has translated these Atlas 14 data into Texas rainfall coefficients useful for hydraulic design. In turn, these coefficients will be used to design more effective hydraulic structures. The incorporation of partial and AMS data into the EBDLKUP-2019 tool, and associated updates to the TxDOT *Hydraulic Design Manual*, will provide engineers with additional knowledge of rainfall characteristics within Texas with emphasis on their relevance to hydraulic design. This project also involved collaborations between TxDOT, the TTI project team, and several county flood control districts to determine custom rainfall zones within the state. In this regard, results from the Atlas 14 study were highly anticipated, and when they arrived, were well studied and discussed by practicing hydraulic design engineers.

The Atlas 14 derived Texas rainfall coefficients also enable engineers to predict rainfall intensity for storms with durations as short as 5 minutes (previously the minimum storm duration was 10 minutes). Potentially this could improve hydraulic design for watersheds with short t_c (e.g., small, urban watersheds with impervious surfaces).

Management and Policy

In addition to providing new Atlas 14 derived Texas rainfall coefficients, this project has delivered recommended amendments to the TxDOT *Hydraulic Design Manual*, Google Earth KML files that engineers can use to determine the appropriate rainfall zone for their project, and instructional videos and webinars. The project has harnessed the improved spatial accuracy of the Atlas 14 data by splitting selected counties into two or more additional rainfall zones that improve the accuracy of design storm rainfall intensity prediction. From a management and policy perspective, maintaining a finite set of rainfall zones is important because it enables the rainfall intensities used in designs to be easily checked. Additionally, by using a finite set of representative rainfall zones, the same Texas rainfall coefficients (as are used in the EBDLKUP-2019) can easily be incorporated into more advanced design tools currently used by TxDOT, such as Bentley OpenRoads designer.

Finally, data generated in this project can be used to determine locations within Texas for which rainfall intensities predicted by older Texas rainfall coefficients (i.e., derived from

Asquith 1998) are markedly different from rainfall intensities predicted by Atlas 14 derived coefficients. In particular, results from this research suggest that Atlas 14 rainfall intensities are, in some cases, up to 50 percent greater than previous predictions in some areas close to the Gulf of Mexico. In such locations, policy may be developed to redesign critical structures to prevent future flooding or to help maintain and preserve existing transportation infrastructure.

Quality of Life

The EBDLKUP-2019 tool and Texas rainfall coefficients developed during this project will improve quality of life by preventing or mitigating flood events. In the case of TxDOT designs flood events could impact transportation infrastructure such as roadways and sidewalks. However, the Texas rainfall coefficients may also be used by other hydraulic design engineers (such as city engineers) to improve hydraulic designs. In urban areas particularly, flooding has the potential to affect homes, businesses, and other private properties.

Surface runoff is a major component of regional hydrological systems and cycles. Ultimately, the runoff from areas adjacent to roadways enters the storm water system, groundwater, or stream and river channels. Flooding can lead to an increase in the sediment and debris load of runoff, which when deposited in natural channels may affect stream flow regimes.

In addition to preventing floods, culverts are increasingly being employed to enable wildlife to cross roads. In such cases, accurate information on rainfall intensity exceedances are useful for ensuring that culverts are sized appropriately to ensure they remain viable crossings even during floods or wet weather (i.e., the culverts do not flood to an extent that they no longer become viable crossings). In some cases, cross culverts are important for maintaining habitat connectivity for aquatic species (e.g., fish and invertebrates). Accurate rainfall estimates can ensure such culverts can be designed to provide flow and volume conditions for this purpose.

Customer Satisfaction and Improved Productivity and Work Efficiency

The direct customer for the EBDLKUP-2019 tool and the associated Atlas 14 derived rainfall coefficients are TxDOT employees involved in hydraulic design. The products of this project will improve the speed and accuracy with which design storm rainfall intensities can be estimated. In addition to EBDLKUP-2019 and the coefficients, researchers have developed Google Earth KML maps that will enable engineers to easily locate projects relative to the rainfall zones used by the EBDLKUP-2019 tool. The project team also developed user manuals and an instructional video for EBDLKUP-2019 that should enable engineers to adapt to the new tool.

Engineering Design Improvement

The outputs from this research project will improve the ability of TxDOT and other statewide engineers to quickly estimate accurate rainfall intensity data for a drainage project. In turn, this will improve the ability of engineers to select the most cost effective structures to maintain transportation function.

One major output of this research project has been a method to determine subcounty rainfall zones. In previous TxDOT hydraulic design tools and guidance, the minimum spatial resolution was a county. In this project, TTI researchers used a sensitivity analysis of the Atlas 14 data to determine a new set of rainfall zones that improve the spatial accuracy of rainfall intensity predictions. The new rainfall zones were assembled to fully use the spatial accuracy of the Atlas 14 data, but at the same time maintain a finite and manageable set of rainfall zones that enable design storm rainfall estimates to be produced rapidly.

The rainfall zones created during this project will ensure that in 240 counties, the rainfall intensities predicted by EBDLKUP-2019 will be less than 10 percent different than the point estimate (at half mile resolution) provided by Atlas 14. In another eight counties, this prediction error will be less than 15 percent. The remaining counties, which contain considerable elevation differences, have a prediction accuracy of 20 percent.

The Atlas 14 project provides 90 percent confidence intervals for all rainfall intensity predictions. Typically, these confidence intervals are approximately 30–40 percent of the most likely rainfall intensity provided by Atlas 14. Therefore, the spatial accuracy of rainfall predictions developed during this project are commensurate with the location specific accuracy reported by the Atlas 14 project. TTI researchers suggest that the improvements in the spatial accuracy of rainfall intensity estimates may also drive improvements in other areas of the rational method used for hydraulic design.

Safety

Flooding caused by poor drainage has implications for traveler safety. Braking distance is two times farther on a wet road compared to a dry road. Hydroplaning can also occur when roads become flooded. Under normal braking conditions, water is forced from underneath tires through pavement surface roughness or tire tread. Hydroplaning occurs when this water can no longer dissipate, and instead it builds up in front of a tire, producing a hydrodynamic force that can lift the tire from the road surface and lead to severe loss of vehicle control.

According to TxDOT's Crash Records Information System (CRIS) between 2010 and 2019, there are 25,729 records of crashes in Texas that involved standing water. These crashes involved a total of 39,855 vehicles (units). Of these crashes, 4,364 (involving 7,292 vehicles) occurred during non-rain, sleet, or snow weather conditions (i.e., weather conditions that suggest that the standard water could have been caused by poor drainage). Of these accidents, 266 resulted in deaths, and 899 resulted in serious injuries.

Sharif et al. (2010) estimates that there were 839 motor vehicle related flood fatalities in Texas between 1959 and 2008. This figure, which translates to approximately 17 deaths per year, is the highest for any state. Sharif et al. (2012) estimate that over half these fatalities occur as a result of travelers driving into flooded roads.

System Reliability

Accurate, location specific rainfall intensity estimates will enable hydraulic engineers to design more appropriate hydraulic structures, which in turn, will reduce the frequency and severity of roadway flooding. According to TxDOT's Drive Texas database between 2014 and 2018, there were 21,068 TxDOT system road closures caused by flooding (5,267 per year).

Road closures affect system reliability by affecting planned travel time to destinations. Road closures can affect ordinary travelers (passenger vehicles) but can also affect access to areas by emergency vehicles. Freight can also be impacted, which can have feedforward effects on the ability of communities to respond to flooding (e.g., availability of water, food, and materials to repair damage).

Increased Service Life/Infrastructure Condition/Reduced Construction, Operations, and Maintenance Cost

According to Ramaswamy and Ben-Akiva (1990), the non-environmental factors that affect the deterioration of pavement can be categorized as:

- Pavement characteristics: pavement strength, layer thickness, base type, surface type.
- Pavement history: time since last rehabilitation, total pavement age.
- Traffic characteristics: average daily traffic, cumulative traffic, traffic mix (percentage of trucks).

In addition to these factors, flooding has multiple dimensions such as the depth and extent of floodwater, or the flow or hydraulic forces of flood water. Although there is considerable evidence that flooding does cause deterioration of pavements, the myriad of factors that drive damage makes it difficult to provide exact predictions or metrics on the way in which flooding impacts the structural integrity or longevity of roads.

However, in a study of road pavement structure following Hurricanes Katrina and Rita, Helali et al. (2008) found that flooded sections of pavements had 2.5–6.5 times higher deflection values than non-flooded sections. Flooded sections deteriorated more quickly and required more maintenance to regain structural integrity. Khan et al. (2017) developed a model of pavement damage under flooding and concluded that rigid pavements are more resilient to flooding than flexible pavements, and that flooded pavements deteriorate less under conditions of low traffic loading.

In addition to direct pavement damage caused by flooding, improperly sized culverts and other drainage systems can themselves fail, causing structural damage to other infrastructure. Perrin and Jhaveri (2003) note that as the road infrastructure ages, so do key supporting infrastructure such as culverts. They note that the interstate system is now approaching 45 years old, and that many culverts on this system used 30- to 50-year design life pipe. As such it is reasonable to assume that the culverts that are at highest risk of failure are those that have exceeded their design life or (have other structural problems); and they are underdesigned given the rainfall intensities suggested by the new Atlas 14 data. Data from this project (and more generally the Atlas 14 data) could be used to identify older or structurally deficient culverts that are also underdesigned according to the new Atlas 14 rainfall intensity estimates.

ECONOMIC FACTORS

In this section, TTI researchers provide data, information, and assumptions to support a quantitative economic assessment of the value of research provided by this project.

Traffic Congestion and System Reliability

Costs of congestion for 2019 (user costs per vehicle hour) (TxDOT 2019):

- Car: $29.35.
- Truck: $39.47.

Between 2014 and 2018, there were an average of 5,267 flood related road closures per year, and the roads were closed on average for 1 day. Assuming an average of a 30-minute detour for each closure, an average Annual Average Daily Traffic (AADT) of 5,000 (TxDOT n.d.) and a truck to passenger car ratio of 15 percent:

Average cost per user per detour:

((15% × 39.47) + (85% × 29.35)) × 30 minutes = $15.43

Total Road Closure Cost:

$15.43 × 5,000 vehicles × 5,267 road closures = $406,349,050

Total Annual Cost Savings:

Assuming improved drainage structures (due to improved rainfall estimates) could reduce these user costs by 0.1 percent, Texas travelers could save $406,349 per year.

Safety

Table 11 shows safety costs for different crash types (FHWA 2019). This information can be combined with data from TxDOT's CRIS crash database detailing crashes occurring with standing water conditions (the CRIS data are categorized by crash severity as per Table 11).

Table 11. FHWA Recommended User Costs Associated with Different Types of Crashes.

Injury Severity Level	Comprehensive Crash Cost
Fatality (K)	$4,008,900
Disabling Injury (A)	$216,000
Evident Injury (B)	$79,000
Fatal/Injury (K/A/B)	$158,200
Possible Injury (C)	$44,900
No Injury (O)	$7,400

Combining these two data sources, the cost of crashes in Texas associated with standing water is approximately $208,392,100 between 2010 and 2019. This estimate purposefully includes only accidents that occurred in standing water conditions, but not during rain, sleet, or snow.

Estimated cost of crashes due to standing water: $23,154,678 per year.

Assuming the results from this project can affect a 0.5 percent reduction in crashes as a result of reducing incidents of standing water on roads, the *estimated annual crash cost savings as a result of improved drainage is* $115,773 per year.

Customer Satisfaction/Engineering Design Improvement/Improved Productivity and Work Efficiency

Every year, TxDOT undertakes approximately 800 hydraulic designs[3] that require the use of the rational method and therefore rainfall intensity estimates. Assuming that the Atlas 14 data is the only option for obtaining up to date, relevant rainfall intensity information, engineers now have two choices for where to obtain this information either: 1) directly from NOAA's precipitation server; or 2) from the EBDLKUP-2019 tool (or other tools) developed through this project.

If an engineer obtains data directly from the Atlas 14 website, it must be manipulated in such a way that Equation A-2 can be fit to the data (researchers will assume that a user has enough knowledge of the rainfall coefficients and statistical fitting routines to be able to fit the data).

As a measure of the utility of the EBDLKUP-2019 tool, the TTI team estimated the time taken for an advanced user to download data from NOAA and fit Equation A-2, versus using EBDLKUP directly (Table 12).

Table 12. Estimated Time Required to Download and Use NOAA Atlas 14 Data with and without Tools Developed during This Project.

Time Download NOAA Atlas 14 data and fit Equation A-2 for each ARI:	Time Taken to Use EBDLKUP-2019
45 minutes	5 minutes

[3] Ab Maamar-Tayeh, P.E., TxDOT Hydraulics engineer (personal communication).

The total effectiveness of this project in terms of improving TxDOT design process is a function of the number of projects designed annually, the average hourly cost of an engineer's time, and the time savings of using the EBDLKUP-2019 tool:

Customer Cost Saving = Number of Projects (annually) × Average Engineer Cost (per hour) × Time Saving (hours)

= 800 × $100 × 0.67 hr = $53,600

ECONOMIC BENEFITS – SUMMARY

TTI researchers have derived three annual cost saving estimates that could arise from the outputs of this research project. Table 13 summarizes these cost savings categories and amounts.

Table 13. Estimated Economic Benefits (Cost Savings) of Using Research Outcomes from This Project Evaluated for Three Benefit Categories.

Benefit Category	**Rationale/Assumptions**	**Cost Savings (per year)**
Traffic Congestion and System Reliability	Improved rainfall estimates will reduce existing road closures (and rerouting) from floods by 0.1%	$406,454
Safety	Improved rainfall estimates will reduce accidents associated with roadway flooding by 0.5%	$115,773
Customer Cost Savings (Design Engineers):	EBDLKUP tool saves time during project design (relative to using Atlas 14 data directly).	$53,600
Total		**$575,827**

TTI researchers used the TxDOT supplied Microsoft Excel spreadsheet to determine a 10-year value of research for this project. The following data were used in these calculations:

- Project Budget (Research Costs): 94,764.
- Net Present Value discount rate: 3 percent.
- Project benefits begin in the second year of the project.

Figure 33 illustrates the results of the VoR calculations. The following metrics summarize the VoR:

- The expected project payback period is 0.16 years.
- The cost benefit ratio of this research is estimated as 49 times the research budget.
- The total savings to TxDOT and the State of Texas is estimated to be over $5.5 million.

Texas Department of Transportation	Project #	0-6980		
	Project Name:	Update Rainfall Coefficients with 2018 NOAA Atlas 14 Rainfall Data		
	Agency:	TTI	Project Budget	$ 94,745
	Project Duration (Yrs)	1.2	Exp. Value (per Yr)	$ 575,827
Expected Value Duration (Yrs)		10	Discount Rate	3%
Economic Value				
Total Savings:	$ 5,653,780	Net Present Value (NPV):		$ 4,677,146
Payback Period (Yrs):	0.164537	Cost Benefit Ratio (CBR, $1 : $___):		$ 49

Years	Expected Value
0	-$85,000
1	$566,082
2	$575,827
3	$575,827
4	$575,827
5	$575,827
6	$575,827
7	$575,827
8	$575,827
9	$575,827
10	$575,827

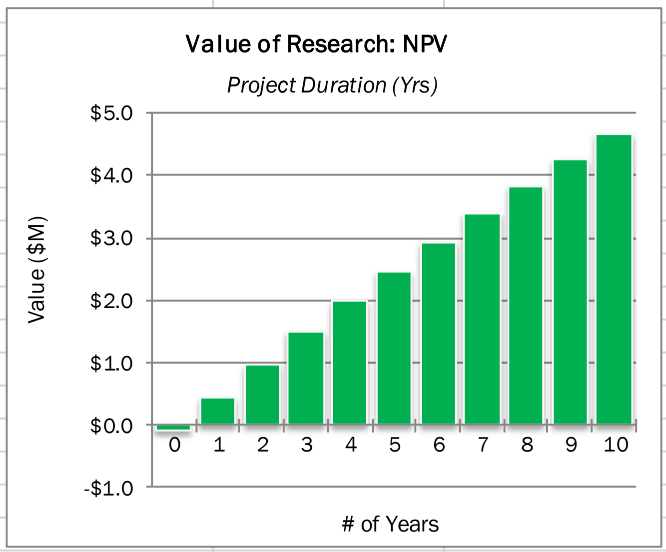

Figure 33. Summary of Value of Research Estimates.