EBDUSA; A Web-Based County-Level Precipitation Intensity-Duration-Frequency Tool for the United States

by

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ABSTRACT

Rainfall Intensity-Duration-Frequency (IDF) models have been developed at least since the 1970s. The IDF models are appealing to design engineers because they provide them with the ability to use a single equation to estimate rainfall intensity at any duration. The development of IDF models involves calculating the model's parameters by finding the best fit of the model curve through an observed set of data points of rainfall depth/intensity. There are several IDF models documented in books and reports during years. In this research, the IDF model proposed by Texas Department of Transportation's Hydraulic Design Manual (TxDOT–HDM) is used to model precipitation frequency data and develop its *ebd* coefficients for most of the counties in the United States. Non-linear programming techniques are used to find the best fit of the IDF model.

This thesis presents the *ebd* analysis R script that constructed for IDF model development. **R** is an open source, statistical programming language and software. This code uses a non-linear minimization approach through `nlm` package for IDF model development.

A web–based application named EBDUSA is designed to deploy the developed *ebd* coefficients and perform the calculation of the intensity of a user-defined duration. This thesis documents the EBDUSA web application development process along with its codes and scripts.

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CHAPTER 1

INTRODUCTION

This thesis documents the development of a web-browser interface called **EBDUSA** that generates rainfall intensity estimates from a parameter database for counties in the United States. The parameter database contains intensity-duration-frequency (IDF) rainfall coefficients generated from various sources of data. Non-linear minimization techniques were applied to create the parameter database. Equation 1.2 from Hydraulic Design Manual of Texas Department of Transportation (TxDOT) [11] is used as the IDF model and its corresponding e, b, and d coefficients are developed.

Previously, the rainfall coefficients database for Texas was updated by Cleveland and others [7] in 2015 by linearizing the non-linear IDF model (Equation 1.2). This database is currently in use through the EBDLKUP-2015v2.1.xlsx spreadsheet tool. In this project, we developed the *ebd* coefficients for all other states of the US using a non-linear programming approach. The IDF model for each county was constructed using non-linear minimization (`nlm`) package in the **R** statistical programing language and environment [17], and corresponding e, b, and d coefficients were generated. The new database of *ebd* values was then deployed as EBDUSA web application tool for use.

The depth-duration-frequency data needed for constructing the IDF models were obtained from the National Weather Service, Precipitation Frequency Data Server (NWS-PFDS). The PFDS is an interactive digital interface of the National Oceanic and Atmospheric Administration (NOAA) Atlas 14 [15] precipitation frequency estimates. The DDF values can be obtained for any location in the United States by providing its coordinates or point-and-click on the map in the PFDS tool. Both annual maximum series and partial duration series methods are available at PFDS. To be consistent with the EBDLKUP-2015 tool, the annual maximum series method was chosen to develop the EBDUSA dataset.

1.1 Motivation

The EBDLKUP-2015.xls spreadsheet tool in common use in Texas is convenient for rapid estimation of rainfall intensity by county for various Annual Recurrence

Intervals (ARI) and arbitrary durations up to 24-hours. However, the tool is only applicable for Texas (or more precisely, there is only a database that fits the estimation tool structure for Texas). Also, the user must download a copy of the spreadsheet, ensure they have the correct and most current copy, and then implement the tool.

Extension to the entire United States is feasible using the NWS-PFDS server for most of the USA, supplemented by state-supplied data for Washington, Texas, Oregon, Idaho, Montana, and Wyoming. A web-browser interface would remove the need to maintain multiple copies (and versioning) and still allow widespread use of the tool. The improvement is that the processing can be done server-side (rather than client-side); however, the number of concurrent queries is likely to be quite small, and once the user queries from the database, the actual computation can be performed on the client's machine.

1.2 Rainfall IDF Concepts

The statistical relationships between precipitation variables are expressed in either Depth-Duration-Frequency (DDF) or Intensity-Duration-Frequency (IDF) models, conveying the same information. The depth of rainfall (P_d) is the accumulated depth in a gaining station over some time interval, duration (T_c) is that time interval, and ARI is related to the probability of observing the depth over the given duration. The alternate form of DDF is to present the magnitude as an intensity which is defined as the ratio of accumulated depth over some averaging time, usually duration, and is shown in Equation 1.1.

$$I = \frac{P_d}{T_c} \tag{1.1}$$

where P_d is the rainfall depth and T_c is the duration (or time of concentration[1]).

The depth of rainfall, P_d, can be found from several sources. The well-known rainfall DDF atlas of the United States, known as Technical Paper No. 40 (TP–40) was the first DDF atlas published in 1961 by Hershfield [10]. TP–40 presented maps of the United States displaying isohyetal lines at different durations ranging from 30 minutes to 24 hours and ARIs of 1– to 100–year. Figure 1.1 shows one of the maps

[1]Time of concentration is defined as the time needed for water to flow from the most remote point in a watershed to the outlet of the watershed. Time of concentration is useful in predicting flow rates that would result from hypothetical storms, which are based on statistically derived return periods through IDF curves. Here we are using the time of concentration and rainfall duration interchangeably.

provided by TP–40 depicting the DDF relationship of a 25–year storm and 2–hour duration. For a project design, an engineer would find the map of desired storm ARI and duration, locate the place in which the project resides, and usually interpolate between the depth contour lines to retrieve the corresponding rainfall depth. Once the depth is retrieved, Equation 1.1 can be used to find the intensity.

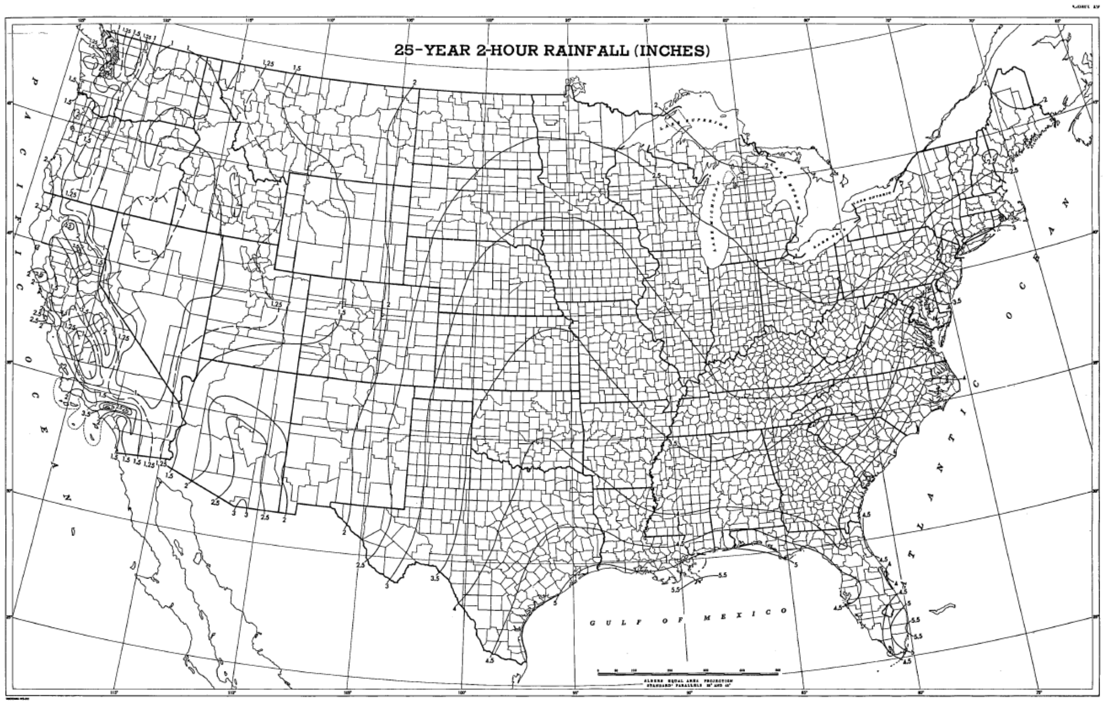


Figure 1.1. DDF atlas of 25–year and 2–hour rainfall, TP–40 [10].

The DDF analyses of rainfall provided precipitation frequency estimates only for a discrete set of durations. Estimation of depth (or intensity) corresponding to durations that are not listed by DDF analyses demands efforts of applying interpolation techniques. On the contrary, IDF models and equations offer the ability to approximate rainfall intensity for any desired duration. The expression of IDF relationships in the form of equations makes them even more user-friendly for designers. With these equations, engineers do not have to retrieve data from tables of rainfall frequency values repetitively.

Section 2.2 provides an overview of different algebraic forms that have been applied for representation of IDF curves. A power-law model is used by TxDOT which appears in Hydraulic Design Manual, 2011 [11] to characterize the precipitation intensity duration relationship. Equation 1.2 expresses this power-law model.

$$I_{ARI;County} = \frac{b}{(T_c + d)^e} \tag{1.2}$$

where I is the intensity, T_c is the time of concentration, b is a scaling factor, d is an offset, and e is an exponent. In customary units, the intensity is in inches per hour, time of concentration is in minutes, b coefficient is in inches, d is in minutes, and e is dimensionless. Although the b and d coefficients have dimensions, they are simply fitting parameters to the power-law model. In this report, the discussion of the units of *ebd* coefficients is omitted to prevent any possible confusion.

The subscript on I in Equation 1.2 is to convey that the function and its related coefficients are a function of frequency (ARI) and location (County).

Equation 1.2 provides the design engineers with the ability to use a single equation over graphical lookup (such as one showed in Figure 1.1) to estimate rainfall intensity at any desired duration. In this research, the rainfall *ebd* coefficients of Equation 1.2 are developed at 2– to 100–years storm and for most of the counties in the United States.

1.3 Thesis Structure

This thesis is organized into four chapters plus several appendices. Chapter 1 is an introduction to the scope of the work, techniques applied, objectives and structure of the thesis. Chapter 2 presents background information on precipitation frequency data and representative models. The analytical methodology is presented in chapter 3 including an overview of techniques for establishing IDF models and web application development. The results and conclusions appear in chapter 4 presenting the outcomes and discussing possible future work. The appendices include US maps of IDF coefficients, **R** script used for IDF model development, and other programming scripts used for EBDUSA web application establishment.

CHAPTER 2

LITERATURE REVIEW

Rainfall-runoff evaluation plays a crucial role in designing adequate drainage systems to minimize impacts within watersheds. Among several methods of estimating peak discharge of rainfall, the rational method is commonly used for small drainage areas of up to about 200 acres [11] due to its simplicity. According to TxDOT, rainfall intensity (I) has a direct influence on estimating runoff as:

$$Q = \frac{CIA}{Z} \tag{2.1}$$

where Q is the maximum rate of runoff in cubic feet per second, C is a runoff coefficient, I is rainfall intensity in inches per hour, A is the drainage area in acres, and Z is a conversion factor [1].

There are several hydrological methods established for ascertaining the peak discharge and intensity. In this section, the methods of determining rainfall coefficients, IDF relationships, and model fit calibration methods are discussed.

2.1 Precipitation Frequency Data

There are several sources available that document rainfall depths values by specific durations and ARIs, providing DDF estimates for different locations in the United States. The first DDF atlas published by Hershlfield in 1961 is the well-known rainfall frequency atlas of the United States known as Technical Paper No. 40 (TP–40)[10]. TP–40 presented maps of the United States displaying isohyetal lines at different durations ranging from 30–minutes to 24 hours and annual recurrence intervals of 1– to 100–years. Figure 1.1 shows one example of the 25–year 2–hour storm map from TP–40.

The first edition of the Hydraulic Manual by Texas Highway Department in 1970 [1] used the rational method, Equation 1.1, and the power-law IDF model, Equation 2.1 for rainfall-runoff analysis in Texas. The *ebd* values of the 1970 edition of the Hydraulic Manual, were replaced in 1975 by new rainfall coefficients developed from

[1] 1.008 for U.S. Customary/English unites, 360 for SI/metric units

a more comprehensive observation of approximately 25 more years of data.

In 1977, a Technical Memorandum HYDRO–35 [9] was published by Fredrick and others for NOAA, supplementing the DDF atlas for approximately 37 states of the United States. HYDRO–35 provided the rainfall frequency estimates for durations ranging from 5 minutes to 1 hour that were not covered in TP–40. Similar to TP–40, HYDRO-35 consists of maps of the United States that display rainfall depth as isohyetal lines for different durations. Also, interpolation of un-mapped durations were discussed in HYDRO–35.

In 1998, United States Geological Survey (USGS) and TxDOT developed a set of rainfall frequency estimates for Texas [2]. In this report, depths are provided through equations based on location, scale, and shape parameters. These parameters were documented as contour maps of Texas at various durations. The development of the parameters was done based on NWS cooperative rain gage data from Louisiana, New Mexico, Arkansan, Oklahoma, and Texas. The data included the same data in TP–40 and HYDRO–35 but supplemented with approximately 25 more years of data.

The DDF Atlas of Texas was created in 2004 by Asquith and Roussel [3]. They used the results of the 1998 report to illustrate DDF Atlas of rainfall depths. Instead of location, scale, and shape parameters, they created atlases based on precipitation depths. The 2004 DDF Atlas provided precipitation depth for storms with durations of 15 minutes to 7 days and ARIs of 2– to 500–year.

NOAA Atlas 2 [13] was one of the notable publications in the 1970s that was built upon TP–40. NOAA Atlas 2 was replaced by the Precipitation Data Frequency Server (PFDS), which provides a point-and-click web portal for precipitation frequency estimates for most of the United States. PFDS is a digital form of NOAA Atlas 14 [15]. NOAA Atlas 14 is missing precipitation frequency estimates for states of Texas, Oregon, Washington, Montana, Idaho, and Wyoming. According to NOAA, the DDF Atlas for Texas will be published in late 2018 through NOAA Atlas 14 Volume 11 and most likely will replace the 2004 DDF Atlas of Texas. NOAA Atlas 14 provides rainfall depths at more ARIs and durations than previous atlases (such as TP–40, HYDRO–35, 2004 DDF Atlas of Texas). Precipitation frequency data are provided at ARIs of 2– to 1000–year and durations of 5 minutes to 60 days.

The PFDS online tool [15] does not provide any specific IDF model and simply presents the depth or intensity values at discrete durations similar to previous DDF atlases. Also, PFDS has no provision for interpolation between these discrete values of durations. Development of IDF models can be helpful for determining intensities at arbitrary durations without needing efforts for interpolation. EBDLKUP-2015.xlsx is a computational spreadsheet tool developed by Cleveland and others in 2015 [7] that calculates intensity using Equation 1.2 for any county in Texas based on user's input time of concentration. This spreadsheet uses a database of *ebd* coefficients developed from Texas DDF Atlas [3]. This research provided the *ebd* for the rest of the states which their DDF data are available at NOAA Atlas 14 – PFDS. Because Texas is missing from NOAA Atlas 14 DDF database as of this writing, the EBDLKUP-2015.xlsx tool's *ebd* coefficients are used for Texas's counties in the new EBDUSA dataset.

2.2 Intensity-Duration-Frequency Models

The variations of rainfall patterns in different geographical regions change the dynamics of IDF models. For each rainfall dataset, a unique IDF model is needed to achieve the best fit curve. The popularity of IDF relationship among design engineers comes from its facility to calculate intensity for any chosen duration. Introduced by Bernard in 1932, IDF relationships have gone through several developments. Some selected IDF models for the United States can be seen in the Equations 2.2 to 2.7 below. The wide variability in models' structure and parameters is noticeable.

- Bernard, 1932 [4]

$$IDF(D,T;k,a,b) = \frac{kT^a}{D^b} \tag{2.2}$$

- Chow and others, 1988 [5]

$$IDF_{\mathcal{F}}^{county}(T_c;c,E,f) = K\frac{c}{T_c^E + f} \tag{2.3}$$

- McCuen, 1989 [12]

$$IDF_{\mathcal{F}}(D;a,b,c,d) = K\begin{cases} \frac{a}{D+B}, & \text{for } T_c \leq 2 \text{ hours} \\ cD^d, & \text{for } T_c > 2 \text{ hours} \end{cases} \tag{2.4}$$

- Wanielista and Eaglin, 1996 [19]

$$IDF_{\mathcal{F}}(T,D;c,s,d,t) = K\frac{cT^s}{(d+D)^t} \tag{2.5}$$

- Los Angeles Department of Public Works, 2006 [8]

$$\frac{I_t}{I_{1440}} = (\frac{1440}{T_c})^{0.47} \tag{2.6}$$

- Texas Department of Transportation, 2014 [16]

$$IDF_{\mathcal{F}}^{county}(T_c; e, b, d) = K\frac{b}{(T_c + d)^e} \tag{2.7}$$

where I or IDF is the rainfall intensity in inches per hour, K is a unit converter, T is the return period in years, variables T_c and D to the left of the semicolon are the duration in minutes, and variables $a, b, c, d, D, e, E, f, k, s,$ and t to the right of the semicolons are coefficients. The subscripted variable $\mathcal{F}$ indicates that the corresponding parameters are a function of frequency.

In 1989, Richard McCuen provided a general IDF model (Equation 2.4) for the United States. McCuen suggested fitting the curve using least squares [12]. In 1996, Wanielista developed an IDF model (Equation 2.5) for the State of Florida, supported by the Florida Department of Transportation [19]. The Los Angeles Public Works Department published a normalized IDF equation that simply interpolates all other intensities based on the 24-hour rainfall intensity [16]. Their IDF model (Equation 2.6) stands out from the rest due to its lack of parameters.

It is noteworthy that despite their differences, all IDF models are based on nonlinear and multivariate equations. Considering the nonlinear programming of intensity parameters in the proposed R code (*ebd* analysis script), the adaptation of an IDF model would be a matter of changing few lines of code that are directly in charge of IDF equation and its parameters. Such flexibility of nonlinear programming makes the *ebd* analysis script compatible for use in any location. However, in this project, the same IDF model, Equation 1.2, is used for all states.

2.3 Interfaces

To show depth-duration frequency estimates for varying locations, different interfaces were used. As explained in Section 2.1, the first set of DDF values were developed in TP–40 [10]. Figure 1.1 shows one of the maps established in TP–40 depicting DDF values. These maps display the rainfall depth isohyetal lines for any specific duration and ARI. An engineer needs to find the map associated with the desired ARI and duration, locate the project site, and isolate contour lines to find the corresponding rainfall depth. Figure 2.1 shows another example of such maps from Texas 2004 DDF Atlas [3].

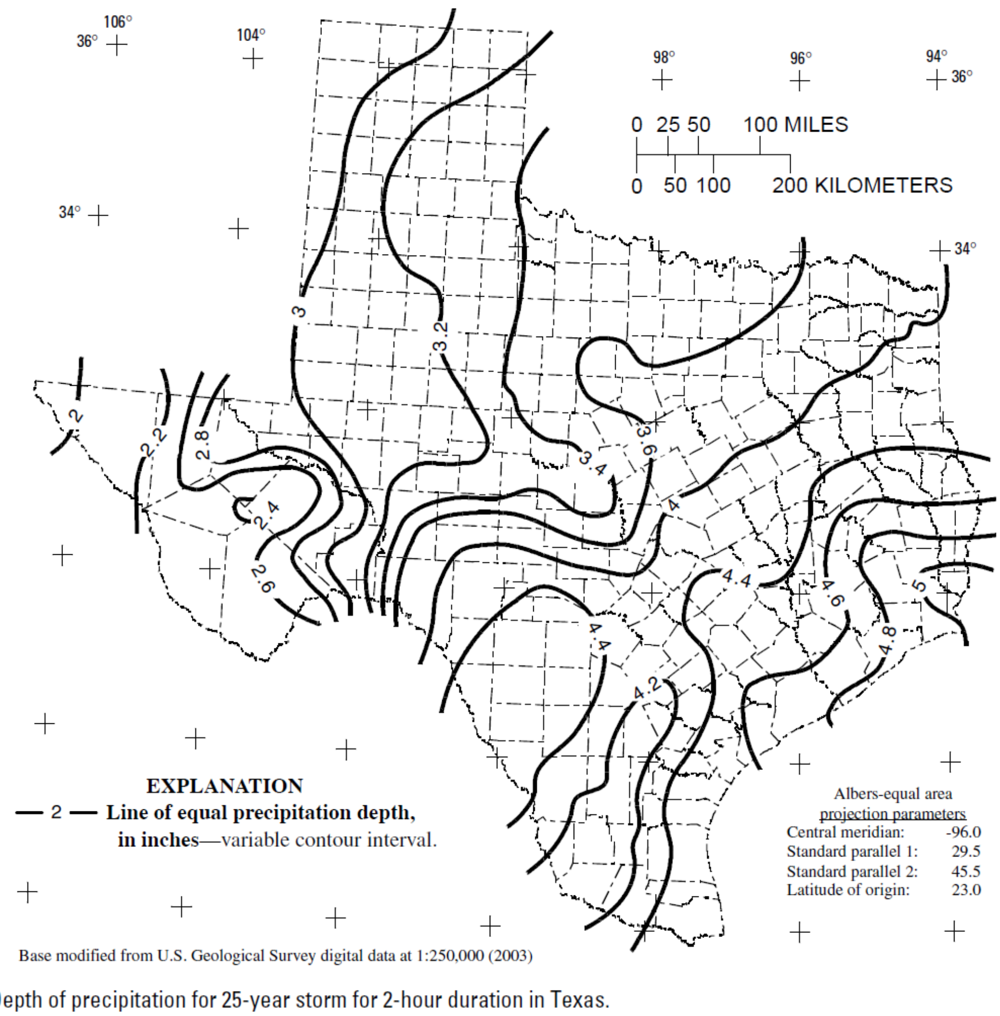


Figure 2.1. Rainfall depth for a 25–year storm , 2–hour duration from Texas 2004 DDF Atlas.

Later, NOAA started to deliver its Atlas 14 of precipitation frequency estimates entirely in digital form. The PFDS acts as a point-and-click interface providing the DDF values for most of the United States. Figure 2.2 shows the interface of PFDS. User can select data type; either precipitation depth or intensity, English or SI units, and underlying series type of partial duration or annual maximum. The desired location can be defined by supplying the latitude and longitude or clicking on the provided map of the United States. When the query is submitted, the DDF values are shown in tabulated form, as in Figure 2.3, or can be download as a .csv file. Notice that interpolation is still needed to obtain precipitation depths related to durations that are not listed the table.

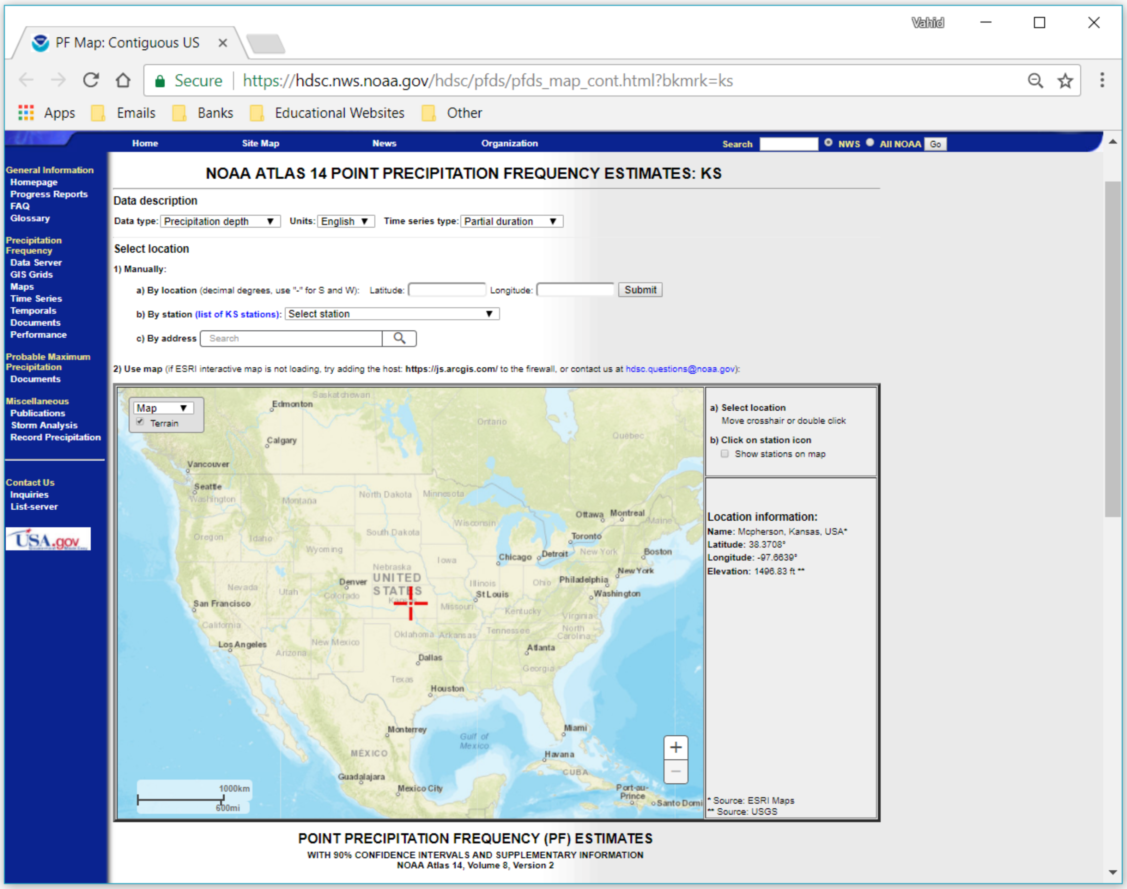
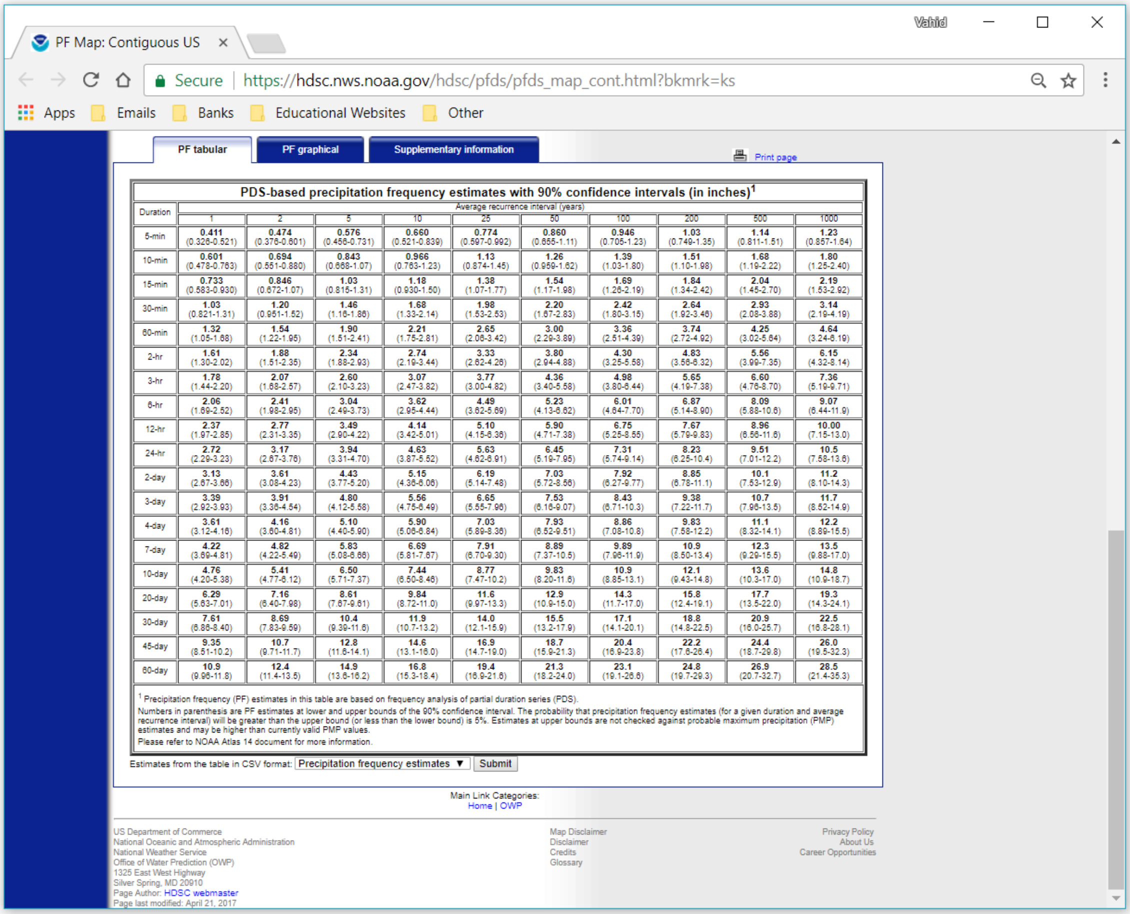


Figure 2.2. NWS–PFDS interface - Latitude and Longitude should be entered for desired location.



PDS-based precipitation frequency estimates with 90% confidence intervals (in inches)[1]

Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
5-min	0.411 (0.326-0.521)	0.474 (0.376-0.601)	0.576 (0.456-0.731)	0.660 (0.521-0.839)	0.774 (0.597-0.992)	0.860 (0.655-1.11)	0.946 (0.705-1.23)	1.03 (0.749-1.35)	1.14 (0.811-1.51)	1.23 (0.857-1.64)
10-min	0.601 (0.478-0.763)	0.694 (0.551-0.880)	0.843 (0.668-1.07)	0.966 (0.763-1.23)	1.13 (0.874-1.45)	1.26 (0.959-1.62)	1.39 (1.03-1.80)	1.51 (1.10-1.98)	1.68 (1.19-2.22)	1.80 (1.25-2.40)
15-min	0.733 (0.583-0.930)	0.846 (0.672-1.07)	1.03 (0.815-1.31)	1.18 (0.930-1.50)	1.38 (1.07-1.77)	1.54 (1.17-1.98)	1.69 (1.26-2.19)	1.84 (1.34-2.42)	2.04 (1.45-2.70)	2.19 (1.53-2.92)
30-min	1.03 (0.821-1.31)	1.20 (0.951-1.52)	1.46 (1.16-1.86)	1.68 (1.33-2.14)	1.98 (1.53-2.53)	2.20 (1.67-2.83)	2.42 (1.80-3.15)	2.64 (1.92-3.46)	2.93 (2.08-3.88)	3.14 (2.19-4.19)
60-min	1.32 (1.05-1.68)	1.54 (1.22-1.95)	1.90 (1.51-2.41)	2.21 (1.75-2.81)	2.65 (2.06-3.42)	3.00 (2.29-3.89)	3.36 (2.51-4.39)	3.74 (2.72-4.92)	4.25 (3.02-5.64)	4.64 (3.24-6.19)
2-hr	1.61 (1.30-2.02)	1.88 (1.51-2.35)	2.34 (1.88-2.93)	2.74 (2.19-3.44)	3.33 (2.62-4.26)	3.80 (2.94-4.88)	4.30 (3.25-5.58)	4.83 (3.56-6.32)	5.56 (3.99-7.35)	6.15 (4.32-8.14)
3-hr	1.78 (1.44-2.20)	2.07 (1.68-2.57)	2.60 (2.10-3.23)	3.07 (2.47-3.82)	3.77 (3.00-4.82)	4.36 (3.40-5.58)	4.98 (3.80-6.44)	5.65 (4.19-7.38)	6.60 (4.76-8.70)	7.36 (5.19-9.71)
6-hr	2.06 (1.69-2.52)	2.41 (1.98-2.95)	3.04 (2.49-3.73)	3.62 (2.95-4.44)	4.49 (3.62-5.69)	5.23 (4.13-6.62)	6.01 (4.64-7.70)	6.87 (5.14-8.90)	8.09 (5.88-10.6)	9.07 (6.44-11.9)
12-hr	2.37 (1.97-2.85)	2.77 (2.31-3.35)	3.49 (2.90-4.22)	4.14 (3.42-5.01)	5.10 (4.15-6.36)	5.90 (4.71-7.38)	6.75 (5.25-8.55)	7.67 (5.79-9.83)	8.96 (6.56-11.6)	10.00 (7.15-13.0)
24-hr	2.72 (2.29-3.23)	3.17 (2.67-3.76)	3.94 (3.31-4.70)	4.63 (3.87-5.52)	5.63 (4.62-6.91)	6.45 (5.19-7.95)	7.31 (5.74-9.14)	8.23 (6.25-10.4)	9.51 (7.01-12.2)	10.5 (7.58-13.6)
2-day	3.13 (2.67-3.66)	3.61 (3.08-4.23)	4.43 (3.77-5.20)	5.15 (4.36-6.06)	6.19 (5.14-7.48)	7.03 (5.72-8.56)	7.92 (6.27-9.77)	8.85 (6.78-11.1)	10.1 (7.53-12.9)	11.2 (8.10-14.3)
3-day	3.39 (2.92-3.93)	3.91 (3.36-4.54)	4.80 (4.12-5.58)	5.56 (4.75-6.49)	6.65 (5.55-7.96)	7.53 (6.16-9.07)	8.43 (6.71-10.3)	9.38 (7.22-11.7)	10.7 (7.96-13.5)	11.7 (8.52-14.9)
4-day	3.61 (3.12-4.16)	4.16 (3.60-4.81)	5.10 (4.40-5.90)	5.90 (5.06-6.84)	7.03 (5.89-8.36)	7.93 (6.52-9.51)	8.86 (7.08-10.8)	9.83 (7.58-12.2)	11.1 (8.32-14.1)	12.2 (8.89-15.5)
7-day	4.22 (3.69-4.81)	4.82 (4.22-5.49)	5.83 (5.08-6.66)	6.69 (5.81-7.67)	7.91 (6.70-9.30)	8.89 (7.37-10.5)	9.89 (7.96-11.9)	10.9 (8.50-13.4)	12.3 (9.29-15.5)	13.5 (9.88-17.0)
10-day	4.76 (4.20-5.38)	5.41 (4.77-6.12)	6.50 (5.71-7.37)	7.44 (6.50-8.46)	8.77 (7.47-10.2)	9.83 (8.20-11.6)	10.9 (8.85-13.1)	12.1 (9.43-14.8)	13.6 (10.3-17.0)	14.8 (10.9-18.7)
20-day	6.29 (5.63-7.01)	7.16 (6.40-7.98)	8.61 (7.67-9.61)	9.84 (8.72-11.0)	11.6 (9.97-13.3)	12.9 (10.9-15.0)	14.3 (11.7-17.0)	15.8 (12.4-19.1)	17.7 (13.5-22.0)	19.3 (14.3-24.1)
30-day	7.61 (6.86-8.40)	8.69 (7.83-9.59)	10.4 (9.39-11.6)	11.9 (10.7-13.2)	14.0 (12.1-15.9)	15.5 (13.2-17.9)	17.1 (14.1-20.1)	18.8 (14.8-22.5)	20.9 (16.0-25.7)	22.5 (16.8-28.1)
45-day	9.35 (8.51-10.2)	10.7 (9.71-11.7)	12.8 (11.6-14.1)	14.6 (13.1-16.0)	16.9 (14.7-19.0)	18.7 (15.9-21.3)	20.4 (16.9-23.8)	22.2 (17.6-26.4)	24.4 (18.7-29.8)	26.0 (19.5-32.3)
60-day	10.9 (9.96-11.8)	12.4 (11.4-13.5)	14.9 (13.6-16.2)	16.8 (15.3-18.4)	19.4 (16.9-21.6)	21.3 (18.2-24.0)	23.1 (19.1-26.6)	24.8 (19.7-29.3)	26.9 (20.7-32.7)	28.5 (21.4-35.3)

[1] Precipitation frequency (PF) estimates in this table are based on frequency analysis of partial duration series (PDS).

Numbers in parenthesis are PF estimates at lower and upper bounds of the 90% confidence interval. The probability that precipitation frequency estimates (for a given duration and average recurrence interval) will be greater than the upper bound (or less than the lower bound) is 5%. Estimates at upper bounds are not checked against probable maximum precipitation (PMP) estimates and may be higher than currently valid PMP values.

Please refer to NOAA Atlas 14 document for more information.

Estimates from the table in CSV format: Precipitation frequency estimates ▼ Submit

Main Link Categories:
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National Weather Service
Office of Water Prediction (OWP)
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Figure 2.3. NWS–PFDS output results of DDF values.

The EBDLKUP-2015.xlsx spreadsheet tool contains the *ebd* rainfall coefficients for counties in Texas. The tool interface is shown in Figure 2.4. The user can define the units, the county, and the desired time of concentration for calculating the intensity based on Equation 1.2 with corresponding coefficients provided by the tool. Figure 2.4 shows the results of intensity estimates for Lubbock County for a 15–minutes duration storm.

An interface very similar to the EBDLKUP-2015.xlsx tool was used in this project to provide the intensity estimates and rainfall coefficients for most of the counties in the United States through the EBDUSA tool. Instead of a spreadsheet, a web application was designed to deliver the information to the user. The EBDUSA web application tool interface is discussed in Chapter 4

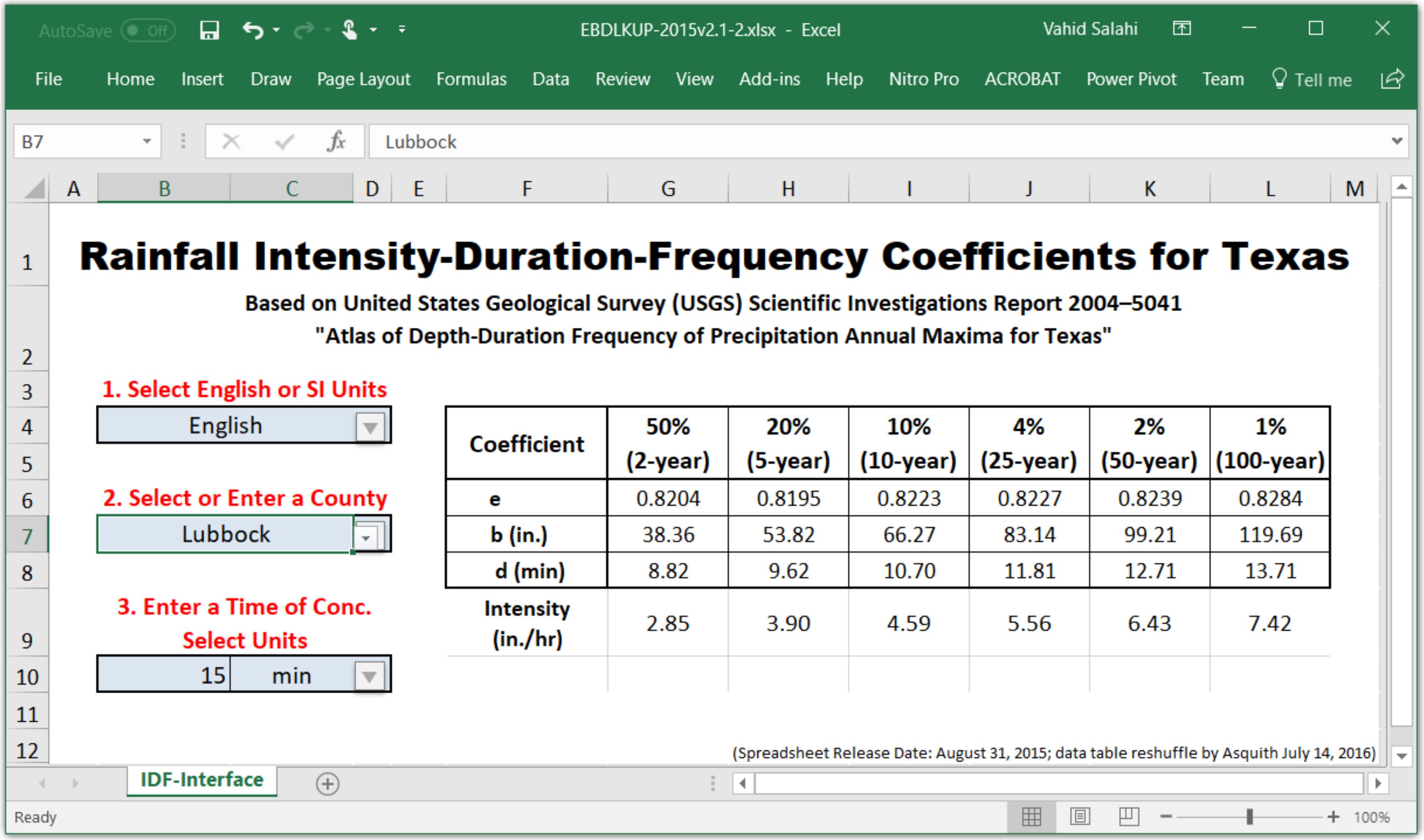


Figure 2.4. EBDLKUP-2015 tool interface.

CHAPTER 3

METHOD OF ANALYSIS

This chapter presents the process of generating *ebd* rainfall coefficients using non-linear programming techniques using **R**. Depth-duration-frequency data tables from NWS-PFDS are the source of precipitation frequency estimates of the analysis. The proposed **R** script and the `nlm` package used to develop the IDF models are discussed here. To illustrate the process, the development of IDF model and *ebd* coefficients for Lincoln County, OK is presented. Later on, the EBDUSA web application tool development is explained. Scripting languages such as HTML, CSS, and JavaScript that were used to design the interface of the tool are discussed. Inter-communications between client-side and server-side using a PHP script are demonstrated.

3.1 Data Preparation

Precipitation depth-duration-frequency data are available for most of the states in the United States from National Weather Service, Precipitation Frequency Data Server (NWS–PFDS). Using latitude and longitude of any location in the United States, the DDF data for a set of different Annual Recurrence Intervals (ARI) and durations can be downloaded from NWS-PDFS. The results of the precipitation frequency data server were supplied to the author-written R-script to process and generate the set of values of e, b, and d (ebd) that represent coefficients of the hyperbolic representation of the intensity-duration-frequency behavior for rainfall. The EBD values were collected into a database for the entire United States that serves as a data source for a web interface that can access that database and generate rainfall intensity estimates for different annual recurrence intervals from 2– to 100–year and durations up to 24 hours for anywhere in the USA.

Texas, Oregon, Washington, Idaho, Wyoming, and Montana are currently missing the DDF values in the NWS PFDS. According to the Hydrometeorological Design Studies Center (HDSC) and NWS-PFDS, the updated precipitation frequency estimates for the state of Texas will be published in NOAA Atlas 14 Volume 11 in late 2018. Also, the Office of Weather Prediction of NOAA is working with several northwestern state agencies to extend NOAA Atlas 14 coverage to the remaining five states.

Cleveland and others in 2015 [7] developed the EBD values for Texas and therefore, these values were taken from EBDLKUP-2015v2.1.xls database and imported into the EBDUSA database.

Once the precipitation frequency estimates get updated for the five remaining states, then the *ebd* analysis script must be applied to develop these states' corresponding *ebd* values and update the entire USA database.

3.2 Non-linear Model in R - Building the EBDUSA Database

The EBDUSA database was built using county-by-county interrogation of the NWS–PFDS to obtain precipitation-depth frequency estimates using annual maximum series estimates. The latitude and longitude for each county's centroid in the USA were obtained from Tucows, Inc. [18]. A handful of counties in the Tucows, Inc. database were incorrectly located, as several counties in some states such as Hawaii, Florida, Michigan and California were off shore. These counties were detected by performing spatial analysis in ArcGIS and comparing the provided latitude and longitude of counties against the geometrically-calculated counties' centroids in ArcGIS.

The incorrect centroids were manually modified and adjusted using other sources of latitude-longitude information or from calculated centroids in ArcGIS. After the data cleaning process, 3142 counties and county-equivalents were considered for the parameter database containing 3007 counties, 64 parishes, 18 boroughs, 11 census areas, 41 independent cities, and the District of Colombia. Figure 3.1 depicts the USA counties and their centroids.

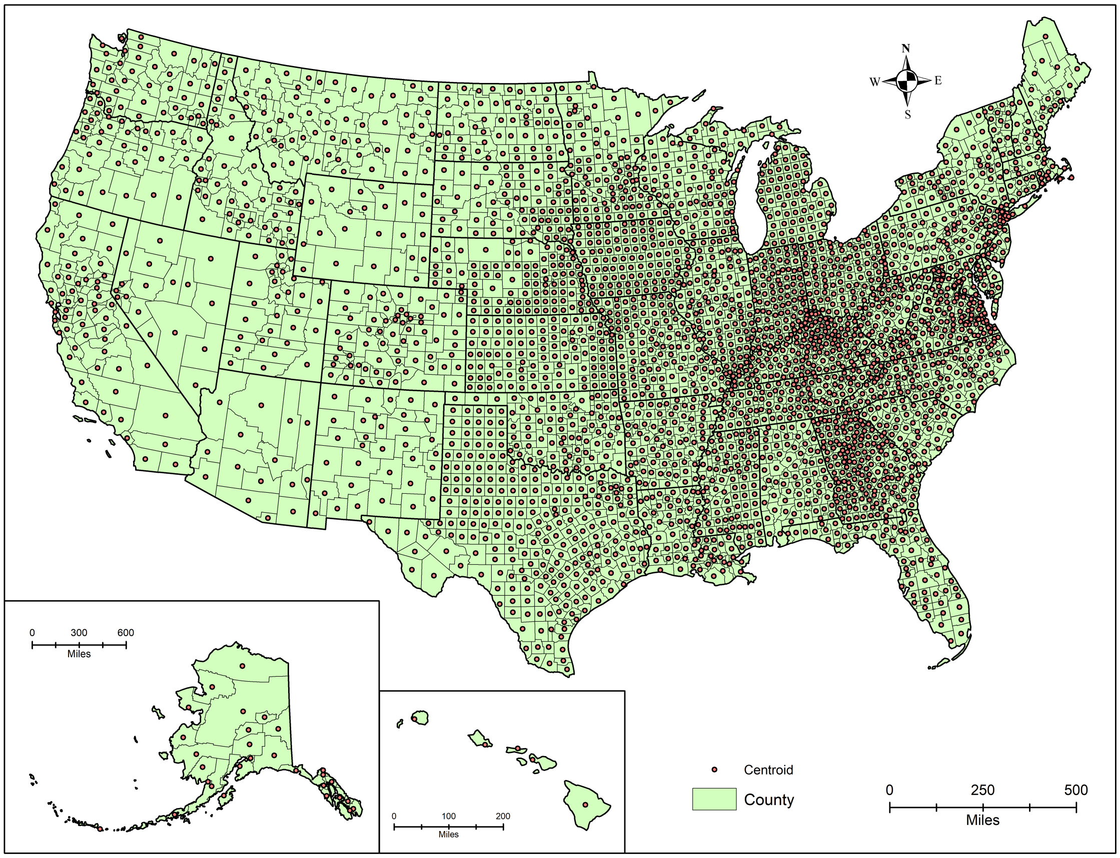


Figure 3.1. USA counties's geometrical centroids.

Once the counties' centroids database was finalized, the DDF data for every county's centroid were downloaded from NWS–PFDS. The DDF data contained a set of different annual recurrence intervals of 2– to 100–year and durations of 5–minutes to 60–days. Each county file was processed using the *ebd* analysis script that parsed the file and extracted the estimated depths for 2–, 5–, 10–, 25–, 50–, and 100–year recurrence intervals and durations of 5–, 10–, 15–, 30–, 60–, 120–, 180–, 360–, 720–, and 1440–minutes.

These parsed values were then systematically fit to power-law IDF Equation 3.1 for each recurrence interval using the non-linear minimization tool in R.

$$I = \frac{b}{(T_c + d)^e} \tag{3.1}$$

Appendix 4.3 presents the *ebd* analysis R script that reads the county file and fits the equation.

3.2.1 Model development in R

In this section, a brief overview of non-linear programming in **R** and the primary functions used for IDF model development is discussed. **R** was chosen for this project because of its advanced statistical packages. The `nlm` (non-linear minimization) package is used to minimize the Sum of Squared Errors (SSE) of predicted and observed intensities.

In the *ebd* analysis script, the `nlm` function is called six times to perform the non-linear optimization calculations for each ARI of all six periodical categories and to estimate the corresponding *ebd* values. In using `nlm` package, the most important parameter in the function is the initial guess of the set of *ebd* parameters.

Non-linear minimization is strongly dependent on the initial estimated set of parameter values and an unreasonable initial parameter estimates can cause the algorithm to drift off the state space model and result in poor estimates. To avoid such problem, an initial guess of the parameters is made only once for the first ARI and the resultant estimated parameters were used as initial guesses of *ebd* parameters for the next run of `nlm` function of the next ARI. By doing so, a reasonable convergence is obtained for each ARI. The same initial starting values of 0.004 were chosen for all e, b, and d to call `nlm` function for each county. This initial parameter set was concluded to be sufficient after using different sets of starting parameters and performing several numerical experiments.

Although the majority of ARI data converged with the starting parameters of 0.004, there were a handful of counties that need to be supplied with different initial starring values. In such cases, an error message of non-finite value supplied by `nlm` was generated by the `nlm` function, shown in listing 3.1. These counties have to be manually proceeded later when the counties that were amenable to automated processing were completed.

Listing 3.1. 'non-finite value supplied' error message in `nlm` function.

```
Error in nlm(sse, c(x[1], x[2], x[3]), duration, depth100, steptol = 1e-16,  :
        non-finite value supplied by 'nlm'
```

This error is because of the initial values provided to the `nlm` function which are too small. To solve this issue, the code provides users the ability to change the parameters of each coefficient for the starting ARI or separately for each ARI. The starting parameters should be iteratively changed until convergence is achieved for that particular data set.

There is also a warning message in some cases that might appear when running the `nlm` package. This warning message is listed in Listing 3.2. The warning message appears when in the program the derivatives of the function go to zero and the division results in infinite number. The `nlm` package recognizes the zero derivatives as a solution and replaces the `NA` with the next maximum positive value. This message is acknowledged by **R** and can be safely ignored because is not cause for any distress or change.

Listing 3.2. 'NA/Inf replace by maximum positive value' warning message.

```
Warning messages:
In nlm(sse, c(x[1], x[2], x[3]), duration, depth5, steptol = 1e-16,  :
NA/Inf replaced by maximum positive value
```

The *ebd* analysis script starts by parsing the data from the .csv file downloaded from NWS-PFDS for each location/county to extract the DDF values. The ARI of 2– to 100–years and durations of 5–minutes to 24–hours are extracted and used to fit the IDF model. The IDF model (Equation 2.3) is identical to the model presented in within the TxDOT Design Manual [11]. The model, as a depth function (DDF function), is written in **R** and is shown in Listing 3.3.

Listing 3.3. IDF model written in R.

```
depthfunc <- function(tc,eee,bee,dee)
{
dep <- (tc/60)*(bee/((dee+tc)^eee))
return(dep)
}
```

`tc` is the time of concentration (in minutes) and `eee`, `bee`, and `dee` are the parameters e, b, and d. The depth is obtained in inches. With the defined IDF model, the SSE needs to be calculated by taking the squared difference of observed NWS–PFDS depth values and the depths predicted by the IDF model. The SSE function is the objective function which needs to be minimized. The SSE function is written in *ebd* analysis script as shown in Listing 3.4.

Listing 3.4. Sum of Squared Errors function.

```
sse <- function(x,duration,ddfdepth)
{
sum((ddfdepth - depthfunc(duration,x[1],x[2],x[3]))^2)
}
```

In the SSE function, Listing 3.4, the x attribute of the function is a vector of length 3, which x[1], x[2], and x[3] are `eee`, `bee`, and `dee` parameters respectively. The `duration` and `ddfdepth` arguments are durations and corresponding depth values at each ARI provided by NWS-PFDS excel datasheets.

The minimization of SSE is done through the `nlm` package provided by R. Listing 3.5 shows the structure of the `nlm` function and its arguments.

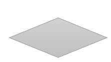
Listing 3.5. `nlm` function structure.

```
nlm(sse,c(x[1],x[2],x[3]),duration,depth,steptol=1e-16, gradtol=1e-6)
```

In Listing 3.5, SSE is the objective function and subscribed `x[1]`, `x[2]`, and `x[3]` variables are a representation of e, b, and d coefficients respectively. `duration` refers to the vector of durations which is constant for each ARI and any county. The `depth` argument is the vector of depths at each ARI corresponding to the vector of durations.

The *ebd* analysis script then proceeds to run the optimization process through each DDF set of values at each ARI for a county and minimize the objective function to generate estimates of *ebd* values for the related DDF dataset. At the end of the code, the obtained *ebd* values are saved as a text file which later are inserted into the EBDUSA database. Figure 3.2 is a flowchart depicting the major portions of the R code process. The description of the shapes used in the flowchart and their meaning are shown in Table 3.1.

Table 3.1. Flowchart shapes and designated descriptions.

Shape	Description
	Designates the entry and exit point of the flowchart
	Defines input or output
	Main process or task
	Asks a question and makes a YES or NO decision
	Determine flow through the chart

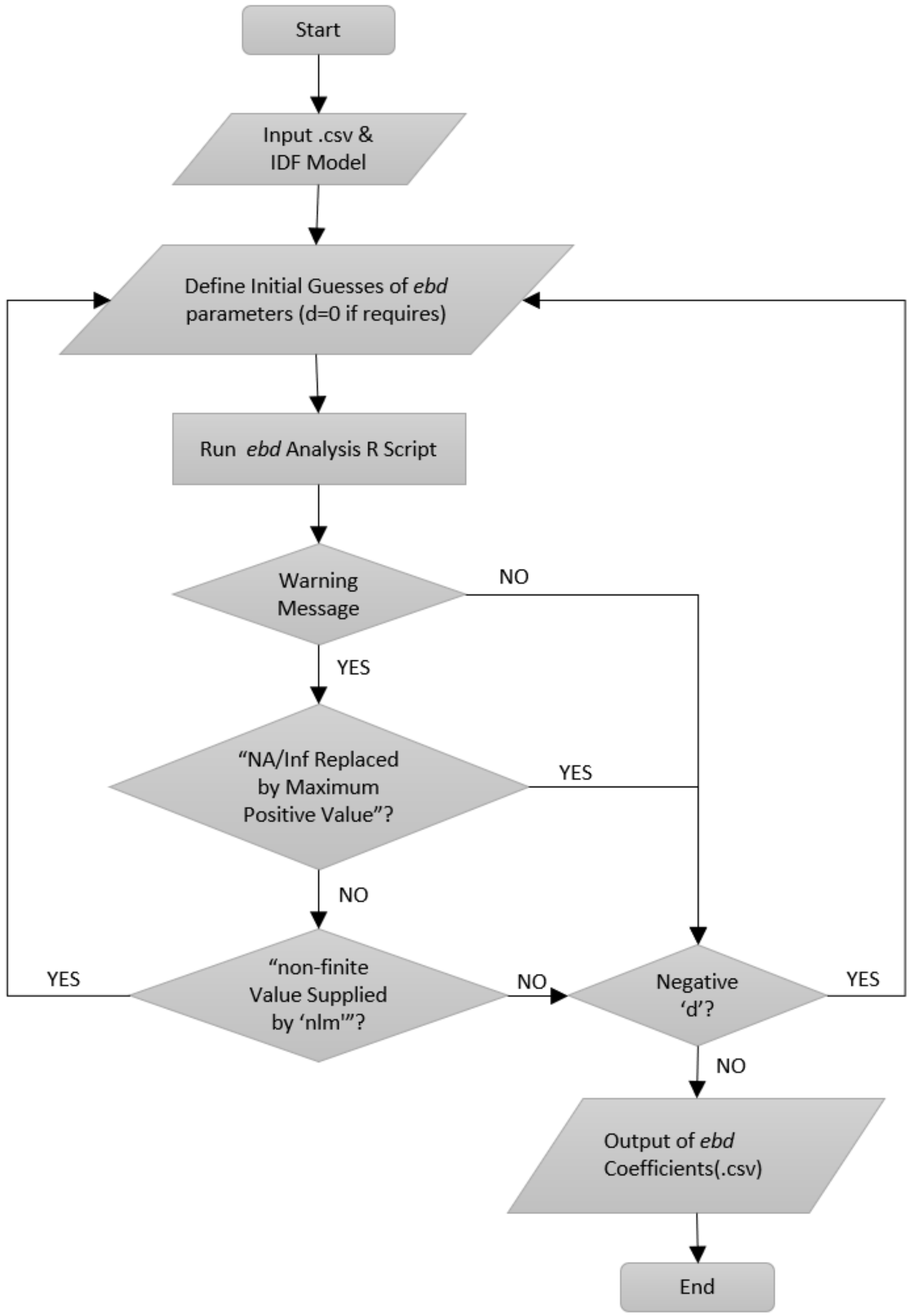


Figure 3.2. Process flowchart of R scripts for developing IDF models.

An illustrative example for Lincoln County, OK is provided in Figure 3.3 through Figure 3.8.

Figure 3.3 shows the EBDUSA database and all its attributes for Lincoln County before supplying its *ebd* values. The database was organized to have the left-most column as a two-character code for the state of interest, in this case OK (Oklahoma). The next column is the county name of Lincoln County and the next two columns are the latitude and longitude in decimal degrees. The next column labeled as ARI for the annual recurrence intervals of 2–, 5–, 10–, 25–, 50–, and 100–year for a given county. The next three columns contain the *ebd* values associated with the IDF model stated in Equation 3.1. Initially, all the *ebd* values are indicated as 999 which means those data have not been processed.

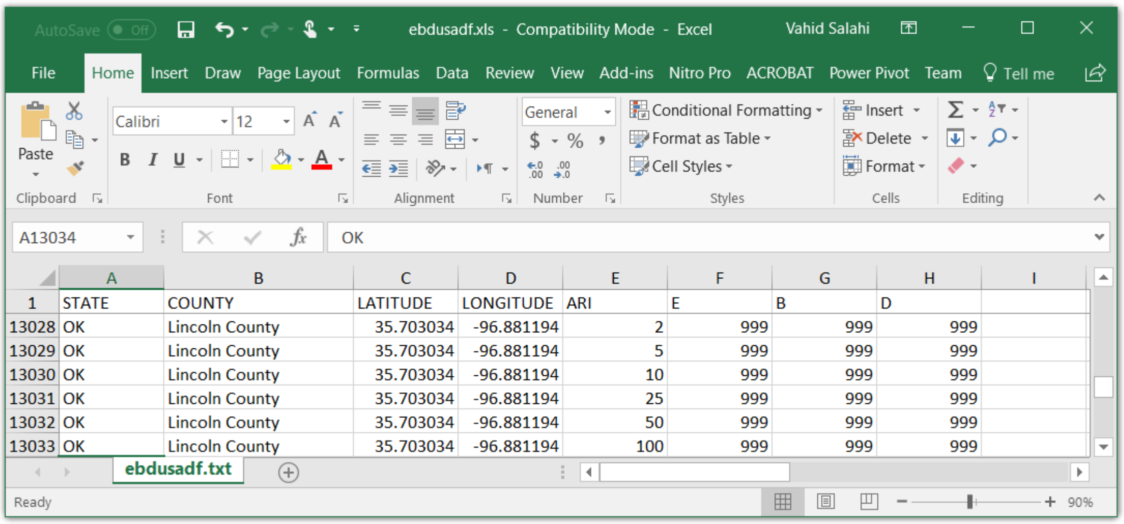


Figure 3.3. EBDUSA database. Latitude and longitude are supplied. The EBD values not yet present.

The latitude and longitude for Lincoln County were used to get the related DDF data from NWS-PFDS as shown in Figure 3.4. It should be noticed that in the "Data Description" section, **Data type**, **Units**, and **Time series type** were chosen respectively as **Precipitation Dept**h, **English**, and **Annual maximum**. After supplying the counties' coordinates, the DDF data were available for download at the bottom of the page. Figure 3.5 presents the DDF dataset of Lincoln County.

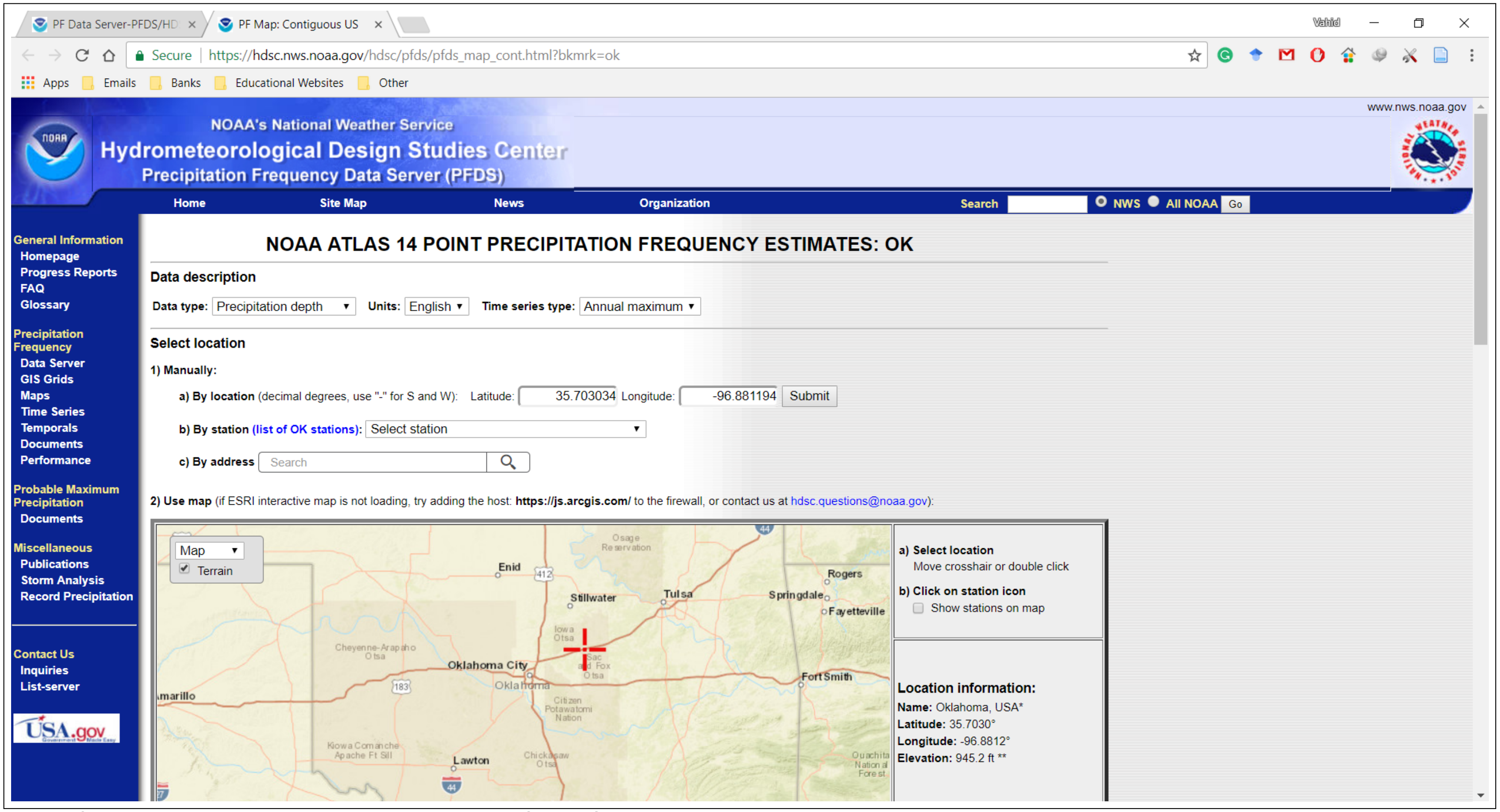
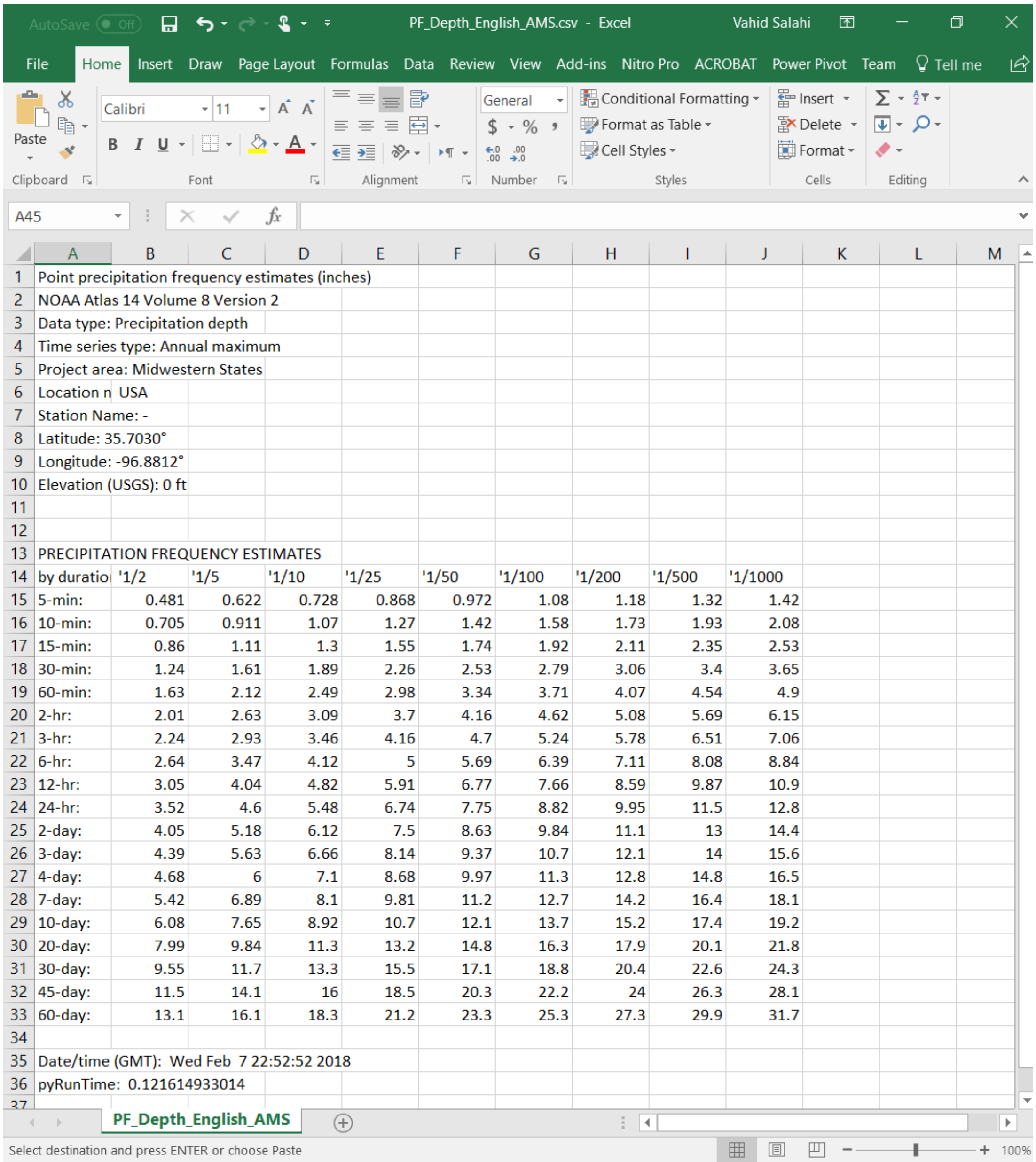


Figure 3.4. Latitude and longitude entered into NWS–PFDS. Annual maximum selected.



	A	B	C	D	E	F	G	H	I	J
1	Point precipitation frequency estimates (inches)									
2	NOAA Atlas 14 Volume 8 Version 2									
3	Data type: Precipitation depth									
4	Time series type: Annual maximum									
5	Project area: Midwestern States									
6	Location n USA									
7	Station Name: -									
8	Latitude: 35.7030°									
9	Longitude: -96.8812°									
10	Elevation (USGS): 0 ft									
11										
12										
13	PRECIPITATION FREQUENCY ESTIMATES									
14	by duratio	'1/2	'1/5	'1/10	'1/25	'1/50	'1/100	'1/200	'1/500	'1/1000
15	5-min:	0.481	0.622	0.728	0.868	0.972	1.08	1.18	1.32	1.42
16	10-min:	0.705	0.911	1.07	1.27	1.42	1.58	1.73	1.93	2.08
17	15-min:	0.86	1.11	1.3	1.55	1.74	1.92	2.11	2.35	2.53
18	30-min:	1.24	1.61	1.89	2.26	2.53	2.79	3.06	3.4	3.65
19	60-min:	1.63	2.12	2.49	2.98	3.34	3.71	4.07	4.54	4.9
20	2-hr:	2.01	2.63	3.09	3.7	4.16	4.62	5.08	5.69	6.15
21	3-hr:	2.24	2.93	3.46	4.16	4.7	5.24	5.78	6.51	7.06
22	6-hr:	2.64	3.47	4.12	5	5.69	6.39	7.11	8.08	8.84
23	12-hr:	3.05	4.04	4.82	5.91	6.77	7.66	8.59	9.87	10.9
24	24-hr:	3.52	4.6	5.48	6.74	7.75	8.82	9.95	11.5	12.8
25	2-day:	4.05	5.18	6.12	7.5	8.63	9.84	11.1	13	14.4
26	3-day:	4.39	5.63	6.66	8.14	9.37	10.7	12.1	14	15.6
27	4-day:	4.68	6	7.1	8.68	9.97	11.3	12.8	14.8	16.5
28	7-day:	5.42	6.89	8.1	9.81	11.2	12.7	14.2	16.4	18.1
29	10-day:	6.08	7.65	8.92	10.7	12.1	13.7	15.2	17.4	19.2
30	20-day:	7.99	9.84	11.3	13.2	14.8	16.3	17.9	20.1	21.8
31	30-day:	9.55	11.7	13.3	15.5	17.1	18.8	20.4	22.6	24.3
32	45-day:	11.5	14.1	16	18.5	20.3	22.2	24	26.3	28.1
33	60-day:	13.1	16.1	18.3	21.2	23.3	25.3	27.3	29.9	31.7
34										
35	Date/time (GMT): Wed Feb 7 22:52:52 2018									
36	pyRunTime: 0.121614933014									

Figure 3.5. Depth estimates by annual maximum series for Lincoln County, OK.

The .csv file of DDF values was downloaded and used as the input file of the *ebd* analysis script. "PF-Depth-English-AMS.csv" was the name of the .csv file downloaded from PFDS and used in the code to read the DDF values. After running the code and producing the *ebd* values, the name of the .csv file was updated to the county's name and kept as records. Figure 3.6 depicts the **RSTUDIO**[1] interface after running the program.

[1]RSTUDIO is an IDE for R

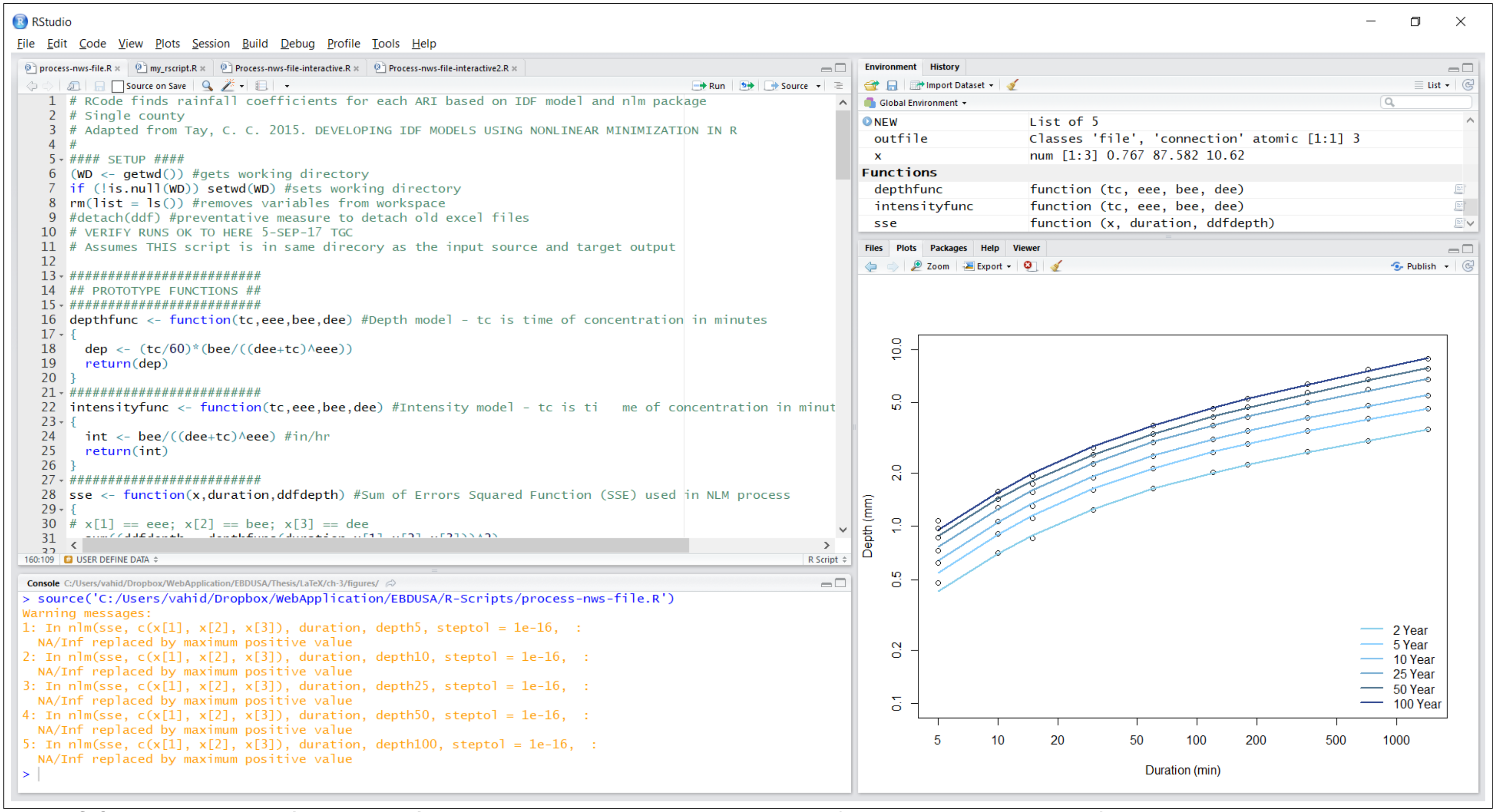


Figure 3.6. Processing the County File. Graph is to guide analyst when the program fails to produce estimates of EBD. Warnings are typical.

The output of the program is a .txt file containing the *ebd* values in rows for each ARI. Columns and rows are in order of parameters of e, b, and d and ARIs of 2–, 5–, 10–, 25–, 50–, and 100–year respectively. The values are inserted in the main EBDUSA database as shown in Figure 3.8.

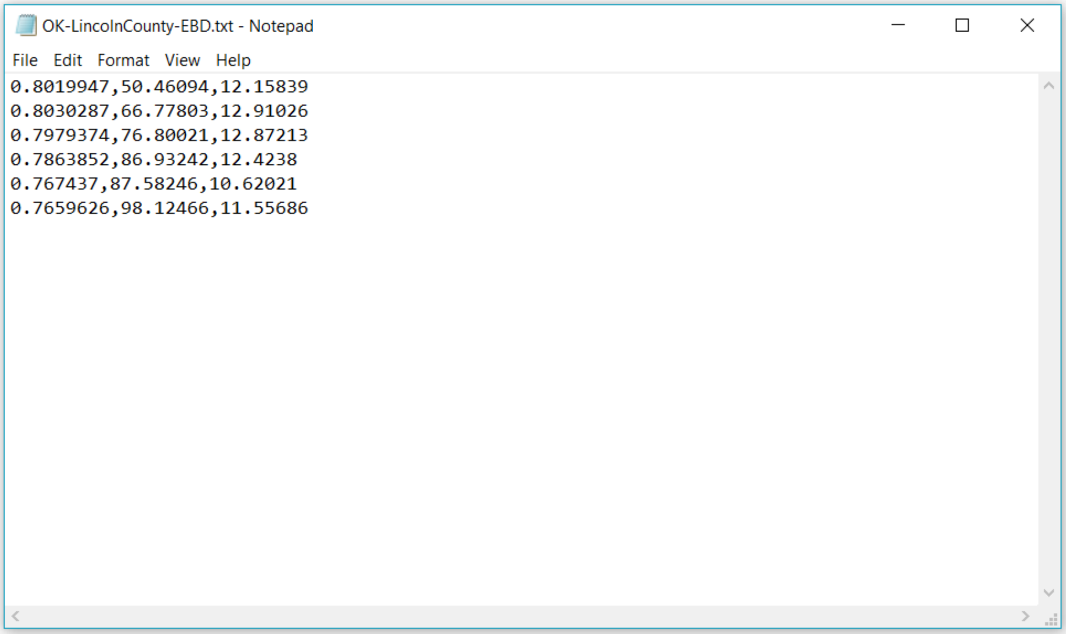
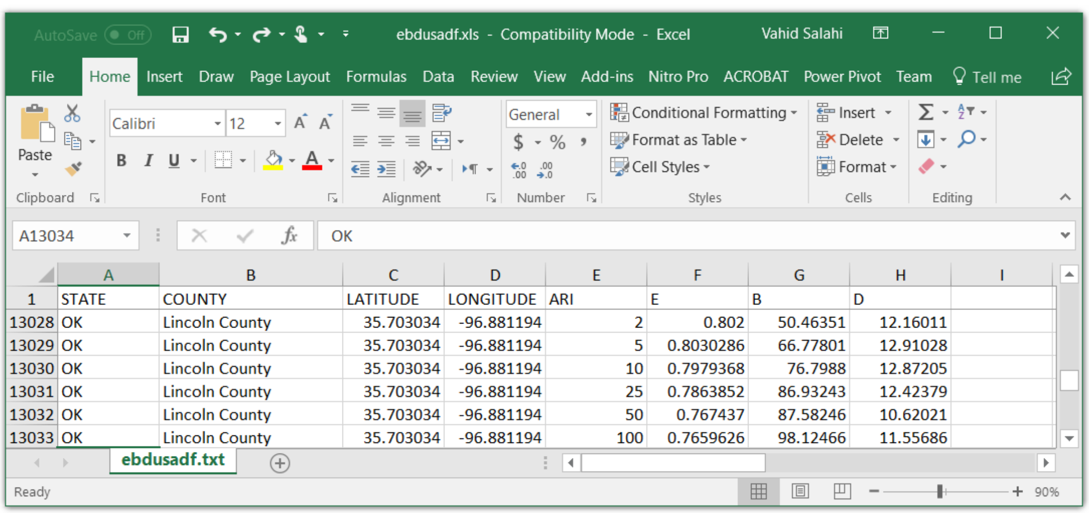


Figure 3.7. EBD output file contents. These are then pasted back into the EBDUSA database to complete the database entries for the specified county.



	A	B	C	D	E	F	G	H
1	STATE	COUNTY	LATITUDE	LONGITUDE	ARI	E	B	D
13028	OK	Lincoln County	35.703034	-96.881194	2	0.802	50.46351	12.16011
13029	OK	Lincoln County	35.703034	-96.881194	5	0.8030286	66.77801	12.91028
13030	OK	Lincoln County	35.703034	-96.881194	10	0.7979368	76.7988	12.87205
13031	OK	Lincoln County	35.703034	-96.881194	25	0.7863852	86.93243	12.42379
13032	OK	Lincoln County	35.703034	-96.881194	50	0.767437	87.58246	10.62021
13033	OK	Lincoln County	35.703034	-96.881194	100	0.7659626	98.12466	11.55686

Figure 3.8. EBDUSA database after processing a specified county.

3.2.2 Estimating Intensity using the EBDUSA Database

Once the *ebd* coefficients of the IDF model regarding of an ARI and a location/-county are known, intensity can be estimated for any duration. By knowing the state, county and, ARI, a user can find the associated *ebd* values in the EBDUSA database and construct the IDF function that allows estimating the intensity for any desired duration. The DDF function was constructed in **R** and shown in Listing 3.3. To calculate the IDF function (IDF model as an intensity function), the depth needs to be divided by time. The IDF function is described in Equation 1.2.

3.3 EBDUSA Web Application Development

In this section, the development of the EBDUSA web application is discussed. This web application was designed to simplify the necessary rainfall intensity estimation for engineers and designers in the rational method or other intensity-based methods. Further guidance on utilization of the web application tool with an example problem can be found in Chapter 4.

The EBDLKUP-2015.xlsx is a spreadsheet tool developed by Cleveland and others [7] which currently is in use with *ebd* rainfall values. This tool uses a database of *ebd* coefficients to calculate intensity based on a given duration and county in Texas. The EBDUSA tool is developed to extend the applicability of EBDLKUP-2015 for all the states/counties in the US. Instead of a spreadsheet, the EBDUSA tool was developed as a web application. The EBDUSA tool is able to calculate the intensity for a given location and duration based on ARIs of 2–, 5–, 10–, 25–, 50–, and 100–year and display the corresponding *ebd* coefficients.

3.3.1 Web Application Development Process

Web applications are dynamic websites stored on remote servers that provide dynamic functionalities such as interacting with client side, connecting to back-end databases, and generating results to the client through a browser. Figure 3.9 shows a schematic of the interactions between the main components of a web application. Web server manages requests from the client side, application server performs the tasks requested from the client, and database server (if a web application requires) stores the information.

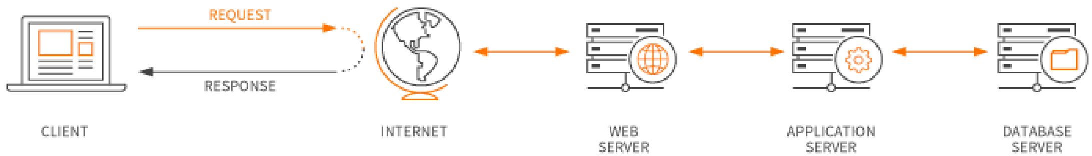


Figure 3.9. Inter-process communication of web applications [14].

The typical web application flow is listed as follows:

1. User prompts a request to the web server over internet usually through a web browser.

2. Web server forwards the request to the proper web application server.

3. The requested tasks are performed by web application server (i.e., PHP). The tasks include processing the data, querying the database, preparing the response, etc. Afterward, the results of the requested data are generated by the web application server.

4. The processed data or requested information are sent to the web server by web application server.

5. The web server responds back to the client with the requested information for display on the browser.

One of the main advantages of a web application is that clients can use the application along as they have access to the Internet and the browser is compatible regardless of the type of operating system or device. This benefit eliminates the compatibilities issues because all users have access to the same version of the application. Also, web applications are not required to be installed on the hard drive, which benefits on space limitations.

The EBDUSA tool was developed as a web application to provide engineers effortless access to *ebd* rainfall coefficients for their design purposes. In the next section, the implementation of the EBDUSA web application tool is discussed.

3.3.2 Implementation

The implementation included two components: Client-Side Scripting/Front End and Server-Side Scripting/Back End. Hyper Text Markup Language (HTML), Cascading Style Sheet (CSS), JavaScript (JS), and Bootstrap are the scripting technologies utilized for developing the web page in the client-side. The later as an HTML, CSS, JS framework was used to design the web page. PHP and **R** are the coding languages used as the application server to process requested data. The index.php which contains the EBDUSA web application scripts is presented in Appendix 4.3. EBDUSA database is uploaded to MySQL database server which corresponding *ebd* coefficient of the user-defined information can be accessed by the web server. The configuration.php is a PHP script which handles the connection between the web server and data server. The configuration.php script is documented in Appendix 4.3.

The user must indicate the name of **State** and **County** through drop-down lists and input **Time of Concentration**. Based on the supplied information, the application server sends a query to the database server to get the corresponding *ebd* coefficients. Based on the *ebd* coefficients, the intensity is calculated in PHP according to the IDF Equation 1.2. The results are sent back to display on the web page showing the intensity estimates and *ebd* coefficients at all six periodical categories of ARI for the specified State and County. In addition, the data are sent to the my-plot.R script (presented in Appendix 4.3) to make a plot of depth-duration for all 6 ARIs. Figure 3.10 shows the inter-process communications of the EBDUSA web application.

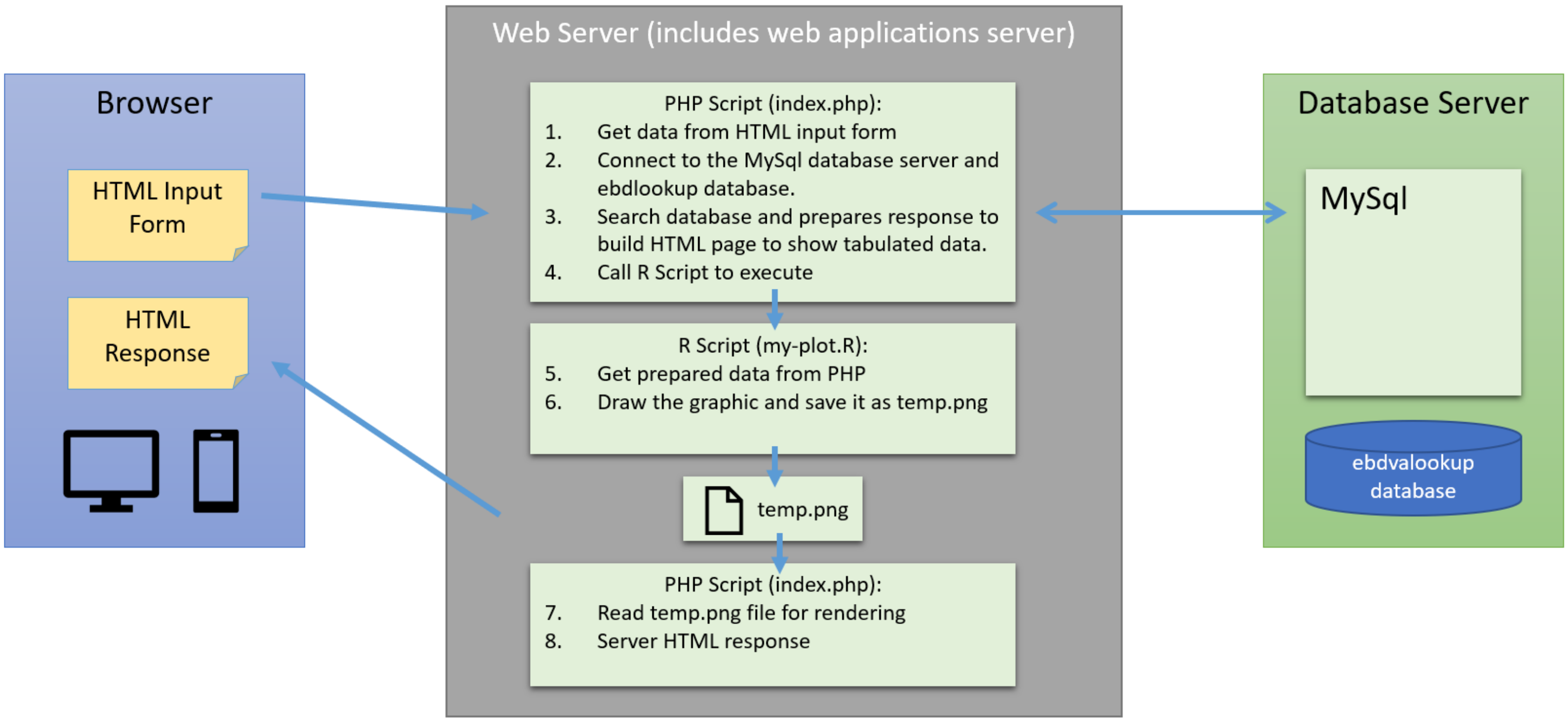


Figure 3.10. EBDUSA web application inter-process communications schematic.

CHAPTER 4

RESULTS AND CONCLUSION

Figure 4.1 shows the EBDUSA web application interface. The interface prompts the user to select a state, a county, and input time of concentration with its units in minutes or hours. The user also can choose the SI or English unit system.

State, county, and time of concentration should be defined before acknowledging any prompt. Otherwise, the webpage will ask the user to select or fill out the empty form. A validator was set for the time of concentrations field to make sure user can only input numeric values as time. The web application provides the *ebd* coefficients for all the 6 ARIs. Based on the defined time of concentration, the intensity is automatically calculated using Equation 1.2. The desired intensity may then be copied and used elsewhere if needed.

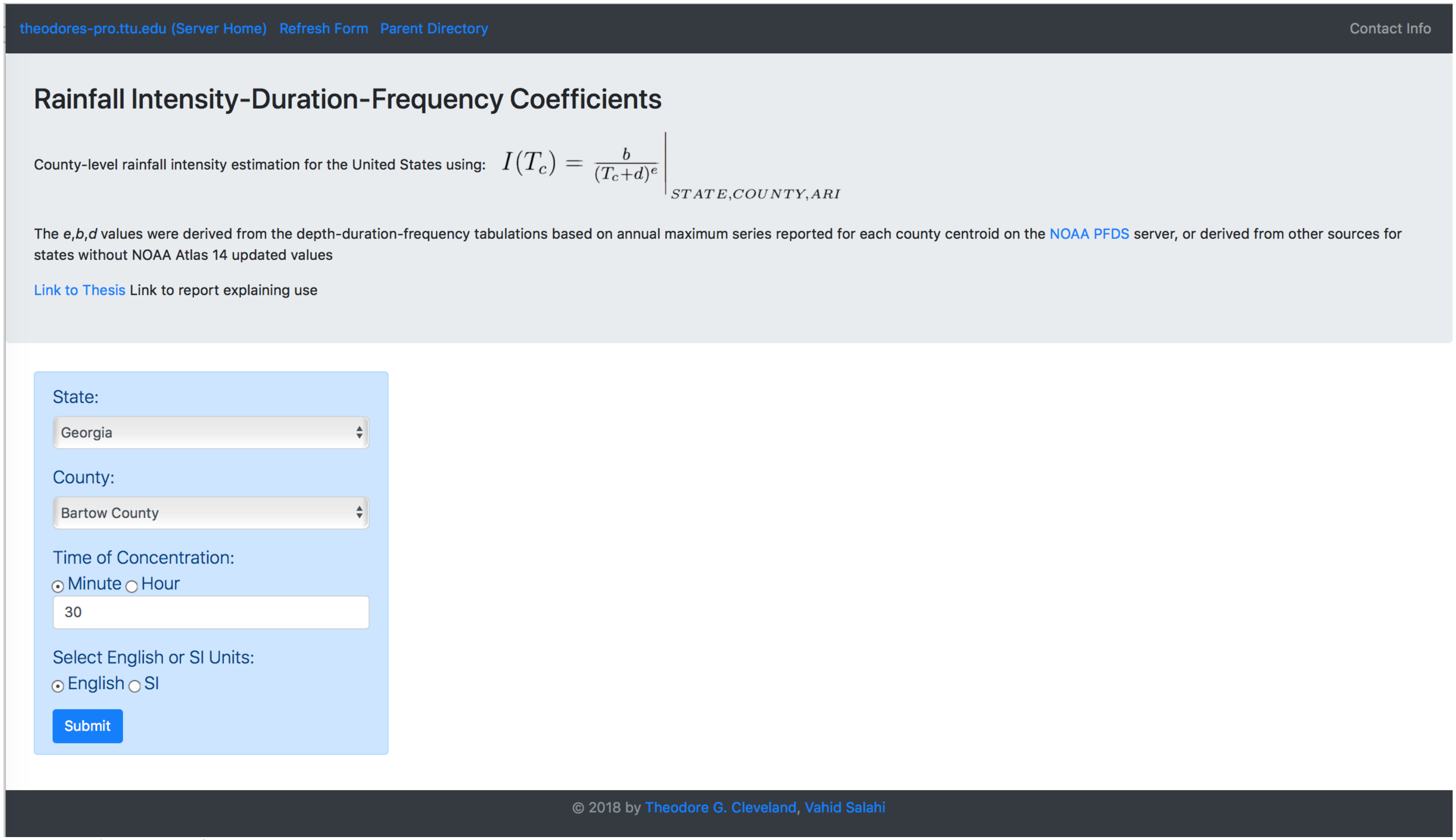


Figure 4.1. EBDUSA tool interface.

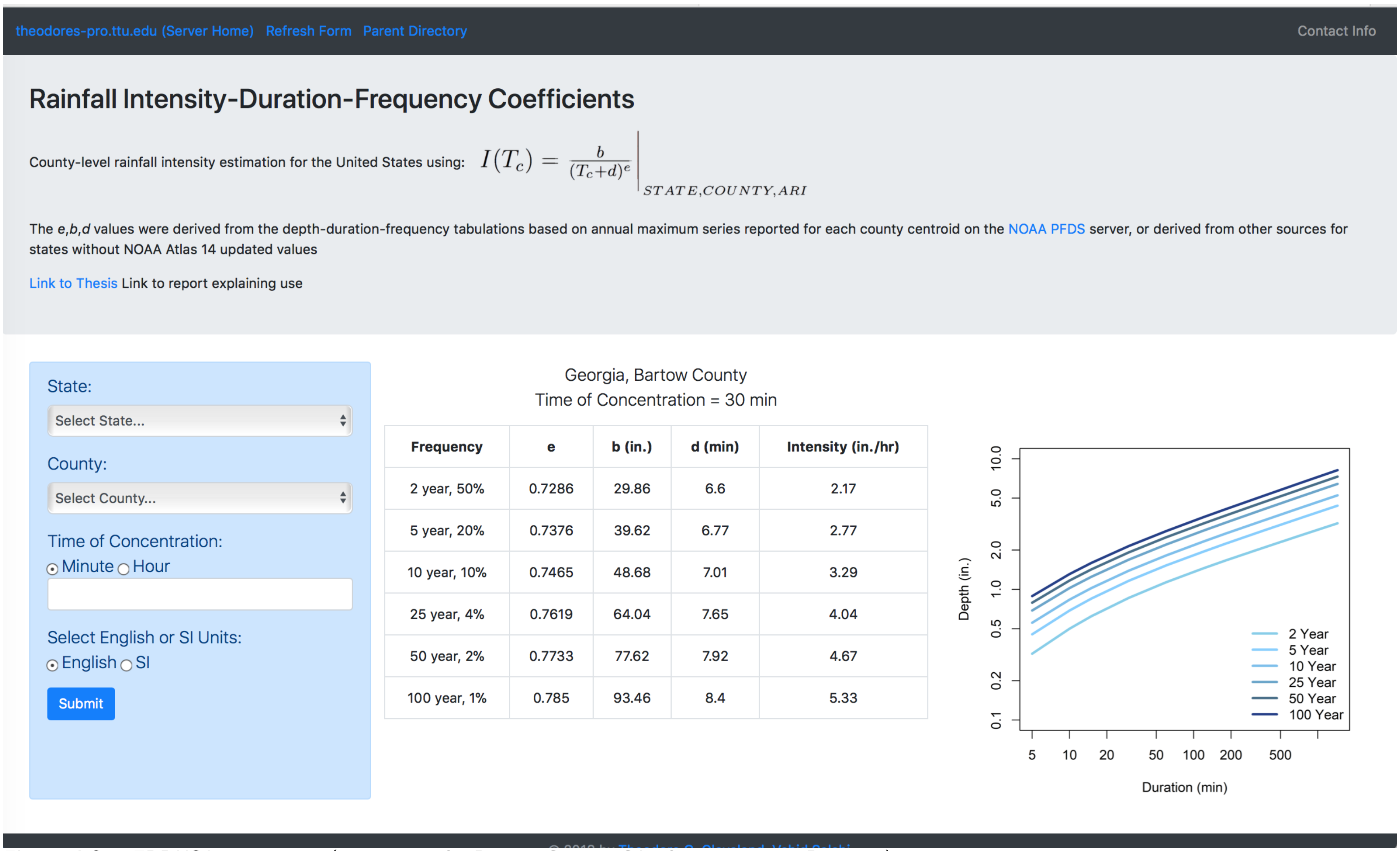


Figure 4.2. EBDUSA tool results (as example for Bartow County, GA of a 30–minutes Duration).

Figure 4.2 shows the results after the prompt was acknowledged to retrieve the *ebd* coefficients and intensity of Bartow County, GA and time of concentration of 30-minutes. The *ebd* values and intensity estimates were tabulated along with a plot of depth-duration in log-log scale for ARI of 2 to 100–years.

The next section presents an example comparing the results from using EBDUSA with equivalent results from the PFDS. The EBDUSA tool is based on PFDS, but differences should arise because of the fitting of an equation to allow for durations between the tabulated values in the PFDS product. Therefore, the results are not expected to be identical, even for identical ARIs and durations (by selecting time values that are equivalent to the discrete values reported on PFDS), but they should be close in terms of either depth or intensity.

4.1 Comparison of EBDUSA and NWS-PFDS

A single county in Georgia was selected. The selected county was Bartow. There is nothing special about the county or state used in this example. Texas was omitted because its values do not derive from the NWS-PFDS server. Figures 4.3 and 4.4 are the products available from the NWS-PFDS that are showing the depth and intensity estimates for Bartow County by duration and Annual Exceedance Probability, AEP (ARI in term of probability). In particular, Figure 4.4 produces estimates of intensity directly, begging the question of "Why bother with EBDUSA"?

AMS-based precipitation frequency estimates with 90% confidence intervals (in inches)[1]

Duration	Annual exceedance probability (1/years)								
	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000
5-min	**0.434** (0.346-0.556)	**0.556** (0.441-0.713)	**0.659** (0.520-0.848)	**0.809** (0.623-1.08)	**0.933** (0.701-1.25)	**1.07** (0.775-1.45)	**1.21** (0.844-1.68)	**1.41** (0.949-1.99)	**1.57** (1.03-2.23)
10-min	**0.636** (0.506-0.814)	**0.814** (0.646-1.05)	**0.965** (0.762-1.24)	**1.18** (0.913-1.58)	**1.37** (1.03-1.83)	**1.56** (1.13-2.13)	**1.77** (1.24-2.45)	**2.06** (1.39-2.92)	**2.30** (1.51-3.27)
15-min	**0.775** (0.617-0.993)	**0.993** (0.788-1.27)	**1.18** (0.929-1.51)	**1.44** (1.11-1.92)	**1.67** (1.25-2.23)	**1.90** (1.38-2.59)	**2.16** (1.51-2.99)	**2.52** (1.69-3.56)	**2.81** (1.84-3.98)
30-min	**1.09** (0.871-1.40)	**1.40** (1.11-1.79)	**1.65** (1.31-2.13)	**2.03** (1.57-2.71)	**2.35** (1.77-3.15)	**2.68** (1.95-3.66)	**3.05** (2.13-4.23)	**3.56** (2.40-5.04)	**3.98** (2.60-5.65)
60-min	**1.42** (1.13-1.82)	**1.81** (1.44-2.32)	**2.14** (1.69-2.75)	**2.62** (2.01-3.48)	**3.01** (2.26-4.03)	**3.43** (2.49-4.66)	**3.87** (2.71-5.37)	**4.51** (3.03-6.37)	**5.02** (3.28-7.12)
2-hr	**1.75** (1.40-2.21)	**2.23** (1.78-2.82)	**2.62** (2.09-3.34)	**3.20** (2.49-4.20)	**3.67** (2.79-4.85)	**4.17** (3.06-5.60)	**4.70** (3.33-6.44)	**5.45** (3.72-7.60)	**6.06** (4.01-8.48)
3-hr	**1.97** (1.59-2.47)	**2.50** (2.01-3.15)	**2.94** (2.35-3.71)	**3.56** (2.78-4.63)	**4.06** (3.10-5.33)	**4.59** (3.40-6.12)	**5.15** (3.67-7.00)	**5.94** (4.08-8.22)	**6.57** (4.39-9.14)
6-hr	**2.42** (1.97-3.00)	**3.04** (2.47-3.79)	**3.54** (2.86-4.42)	**4.24** (3.34-5.44)	**4.80** (3.70-6.21)	**5.38** (4.02-7.07)	**5.99** (4.32-8.02)	**6.83** (4.76-9.32)	**7.50** (5.09-10.3)
12-hr	**2.97** (2.44-3.65)	**3.69** (3.03-4.54)	**4.26** (3.48-5.26)	**5.05** (4.01-6.38)	**5.67** (4.42-7.23)	**6.31** (4.77-8.18)	**6.97** (5.09-9.20)	**7.88** (5.56-10.6)	**8.59** (5.92-11.6)
24-hr	**3.56** (2.96-4.32)	**4.44** (3.68-5.40)	**5.12** (4.22-6.25)	**6.03** (4.83-7.51)	**6.73** (5.30-8.46)	**7.44** (5.69-9.50)	**8.16** (6.03-10.6)	**9.12** (6.52-12.1)	**9.86** (6.90-13.2)
2-day	**4.14** (3.47-4.97)	**5.22** (4.37-6.28)	**6.04** (5.03-7.28)	**7.11** (5.75-8.72)	**7.91** (6.29-9.80)	**8.71** (6.74-11.0)	**9.51** (7.11-12.2)	**10.6** (7.65-13.8)	**11.3** (8.05-15.0)
3-day	**4.51** (3.81-5.38)	**5.63** (4.74-6.72)	**6.48** (5.43-7.76)	**7.62** (6.21-9.30)	**8.49** (6.80-10.5)	**9.37** (7.30-11.7)	**10.3** (7.74-13.1)	**11.4** (8.36-14.8)	**12.3** (8.83-16.2)
4-day	**4.82** (4.09-5.72)	**5.95** (5.03-7.07)	**6.83** (5.74-8.14)	**8.02** (6.57-9.75)	**8.94** (7.20-11.0)	**9.88** (7.75-12.3)	**10.8** (8.23-13.7)	**12.1** (8.94-15.7)	**13.1** (9.48-17.1)
7-day	**5.65** (4.82-6.63)	**6.85** (5.83-8.06)	**7.80** (6.61-9.20)	**9.12** (7.57-11.0)	**10.2** (8.28-12.4)	**11.2** (8.93-13.9)	**12.4** (9.53-15.6)	**13.9** (10.4-17.8)	**15.1** (11.1-19.5)
10-day	**6.38** (5.47-7.44)	**7.67** (6.57-8.96)	**8.70** (7.42-10.2)	**10.1** (8.47-12.2)	**11.3** (9.26-13.7)	**12.5** (9.99-15.3)	**13.7** (10.7-17.2)	**15.5** (11.6-19.7)	**16.8** (12.4-21.5)
20-day	**8.48** (7.35-9.77)	**10.1** (8.73-11.7)	**11.4** (9.80-13.2)	**13.2** (11.1-15.6)	**14.6** (12.1-17.4)	**16.0** (13.0-19.4)	**17.5** (13.8-21.6)	**19.6** (15.0-24.5)	**21.2** (15.9-26.8)
30-day	**10.4** (9.03-11.9)	**12.3** (10.7-14.1)	**13.8** (11.9-15.8)	**15.8** (13.4-18.5)	**17.4** (14.5-20.5)	**19.0** (15.5-22.8)	**20.6** (16.3-25.1)	**22.8** (17.6-28.3)	**24.5** (18.5-30.7)
45-day	**12.9** (11.3-14.6)	**15.2** (13.3-17.3)	**17.0** (14.8-19.4)	**19.3** (16.4-22.4)	**21.0** (17.7-24.6)	**22.8** (18.7-27.0)	**24.5** (19.5-29.6)	**26.7** (20.8-32.9)	**28.4** (21.7-35.3)
60-day	**15.2** (13.4-17.1)	**17.9** (15.7-20.3)	**19.9** (17.4-22.6)	**22.4** (19.1-25.8)	**24.3** (20.4-28.2)	**26.1** (21.5-30.7)	**27.8** (22.3-33.3)	**30.0** (23.4-36.5)	**31.5** (24.3-39.0)

[1] Precipitation frequency (PF) estimates in this table are based on frequency analysis of annual maxima series (AMS).

Numbers in parenthesis are PF estimates at lower and upper bounds of the 90% confidence interval. The probability that precipitation frequency estimates (for a given duration and annual exceedance probability) will be greater than the upper bound (or less than the lower bound) is 5%. Estimates at upper bounds are not checked against probable maximum precipitation (PMP) estimates and may be higher than currently valid PMP values.

Please refer to NOAA Atlas 14 document for more information.

Figure 4.3. PFDS tabular depths by duration and ARI for Bartow County, GA.

Close inspection of Figure 4.4 shows that the tabulated values are for discrete durations. So, if an analyst needs to estimate an intensity corresponding to a duration between the discrete durations, there would be an interpolation challenge. The interpolation would be more challenging when it has to be done on a log-log scale. The intensity-duration curves appear as straighter in log-log scale than otherwise. Therefore, a log-log interpolation should result in a better estimate of intensity for durations not listed in the tabulated data.

AMS-based precipitation frequency estimates with 90% confidence intervals (in inches/hour)[1]

Duration	Annual exceedance probability (1/years)								
	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000
5-min	**5.21** (4.15-6.67)	**6.67** (5.29-8.56)	**7.91** (6.24-10.2)	**9.71** (7.48-12.9)	**11.2** (8.41-15.0)	**12.8** (9.30-17.4)	**14.5** (10.1-20.1)	**16.9** (11.4-23.9)	**18.9** (12.3-26.8)
10-min	**3.82** (3.04-4.88)	**4.88** (3.88-6.27)	**5.79** (4.57-7.45)	**7.10** (5.48-9.46)	**8.20** (6.16-11.0)	**9.36** (6.80-12.8)	**10.6** (7.42-14.7)	**12.4** (8.33-17.5)	**13.8** (9.03-19.6)
15-min	**3.10** (2.47-3.97)	**3.97** (3.15-5.10)	**4.71** (3.72-6.06)	**5.78** (4.45-7.69)	**6.66** (5.01-8.93)	**7.61** (5.53-10.4)	**8.63** (6.03-12.0)	**10.1** (6.78-14.2)	**11.2** (7.34-15.9)
30-min	**2.19** (1.74-2.80)	**2.79** (2.22-3.58)	**3.31** (2.61-4.26)	**4.06** (3.13-5.42)	**4.69** (3.53-6.29)	**5.37** (3.90-7.32)	**6.09** (4.26-8.46)	**7.13** (4.80-10.1)	**7.96** (5.20-11.3)
60-min	**1.42** (1.13-1.82)	**1.81** (1.44-2.32)	**2.14** (1.69-2.75)	**2.62** (2.01-3.48)	**3.01** (2.26-4.03)	**3.43** (2.49-4.66)	**3.87** (2.71-5.37)	**4.51** (3.03-6.37)	**5.02** (3.28-7.12)
2-hr	**0.873** (0.702-1.11)	**1.11** (0.891-1.41)	**1.31** (1.05-1.67)	**1.60** (1.24-2.10)	**1.83** (1.39-2.43)	**2.08** (1.53-2.80)	**2.35** (1.66-3.22)	**2.73** (1.86-3.80)	**3.03** (2.01-4.24)
3-hr	**0.655** (0.529-0.824)	**0.832** (0.670-1.05)	**0.977** (0.783-1.24)	**1.18** (0.925-1.54)	**1.35** (1.03-1.77)	**1.53** (1.13-2.04)	**1.72** (1.22-2.33)	**1.98** (1.36-2.74)	**2.19** (1.46-3.04)
6-hr	**0.403** (0.329-0.502)	**0.508** (0.412-0.632)	**0.591** (0.478-0.738)	**0.708** (0.558-0.908)	**0.801** (0.618-1.04)	**0.899** (0.672-1.18)	**1.00** (0.721-1.34)	**1.14** (0.795-1.56)	**1.25** (0.850-1.72)
12-hr	**0.246** (0.203-0.303)	**0.306** (0.251-0.377)	**0.354** (0.289-0.437)	**0.419** (0.333-0.530)	**0.470** (0.367-0.600)	**0.524** (0.396-0.679)	**0.579** (0.422-0.764)	**0.654** (0.462-0.879)	**0.713** (0.491-0.967)
24-hr	**0.148** (0.123-0.180)	**0.185** (0.153-0.225)	**0.213** (0.176-0.260)	**0.251** (0.201-0.313)	**0.280** (0.221-0.352)	**0.310** (0.237-0.396)	**0.340** (0.251-0.442)	**0.380** (0.272-0.504)	**0.411** (0.287-0.550)
2-day	**0.086** (0.072-0.103)	**0.109** (0.091-0.131)	**0.126** (0.105-0.152)	**0.148** (0.120-0.182)	**0.165** (0.131-0.204)	**0.182** (0.140-0.228)	**0.198** (0.148-0.254)	**0.220** (0.159-0.287)	**0.236** (0.168-0.312)
3-day	**0.063** (0.053-0.075)	**0.078** (0.066-0.093)	**0.090** (0.075-0.108)	**0.106** (0.086-0.129)	**0.118** (0.094-0.145)	**0.130** (0.101-0.163)	**0.142** (0.107-0.181)	**0.159** (0.116-0.206)	**0.171** (0.123-0.224)
4-day	**0.050** (0.043-0.060)	**0.062** (0.052-0.074)	**0.071** (0.060-0.085)	**0.084** (0.068-0.102)	**0.093** (0.075-0.114)	**0.103** (0.081-0.128)	**0.113** (0.086-0.143)	**0.126** (0.093-0.163)	**0.137** (0.099-0.178)
7-day	**0.034** (0.029-0.039)	**0.041** (0.035-0.048)	**0.046** (0.039-0.055)	**0.054** (0.045-0.066)	**0.061** (0.049-0.074)	**0.067** (0.053-0.083)	**0.074** (0.057-0.093)	**0.083** (0.062-0.106)	**0.090** (0.066-0.116)
10-day	**0.027** (0.023-0.031)	**0.032** (0.027-0.037)	**0.036** (0.031-0.043)	**0.042** (0.035-0.051)	**0.047** (0.039-0.057)	**0.052** (0.042-0.064)	**0.057** (0.044-0.072)	**0.064** (0.049-0.082)	**0.070** (0.052-0.090)
20-day	**0.018** (0.015-0.020)	**0.021** (0.018-0.024)	**0.024** (0.020-0.027)	**0.027** (0.023-0.032)	**0.030** (0.025-0.036)	**0.033** (0.027-0.040)	**0.036** (0.029-0.045)	**0.041** (0.031-0.051)	**0.044** (0.033-0.056)
30-day	**0.014** (0.013-0.016)	**0.017** (0.015-0.020)	**0.019** (0.017-0.022)	**0.022** (0.019-0.026)	**0.024** (0.020-0.028)	**0.026** (0.021-0.032)	**0.029** (0.023-0.035)	**0.032** (0.024-0.039)	**0.034** (0.026-0.043)
45-day	**0.012** (0.010-0.014)	**0.014** (0.012-0.016)	**0.016** (0.014-0.018)	**0.018** (0.015-0.021)	**0.019** (0.016-0.023)	**0.021** (0.017-0.025)	**0.023** (0.018-0.027)	**0.025** (0.019-0.030)	**0.026** (0.020-0.033)
60-day	**0.011** (0.009-0.012)	**0.012** (0.011-0.014)	**0.014** (0.012-0.016)	**0.016** (0.013-0.018)	**0.017** (0.014-0.020)	**0.018** (0.015-0.021)	**0.019** (0.015-0.023)	**0.021** (0.016-0.025)	**0.022** (0.017-0.027)

[1] Precipitation frequency (PF) estimates in this table are based on frequency analysis of annual maxima series (AMS).

Numbers in parenthesis are PF estimates at lower and upper bounds of the 90% confidence interval. The probability that precipitation frequency estimates (for a given duration and annual exceedance probability) will be greater than the upper bound (or less than the lower bound) is 5%. Estimates at upper bounds are not checked against probable maximum precipitation (PMP) estimates and may be higher than currently valid PMP values.

Please refer to NOAA Atlas 14 document for more information.

Figure 4.4. PFDS tabular intensities by duration and ARI for Bartow County, GA.

The entire purpose of EBDUSA is to relieve the user of needing to interpolate, yet preserve the depth-duration-frequency behavior of the underlying NWS-PFDS model structure. As explained earlier, this goal can be achieved by having the IDF model. EBDUSA provides the *ebd* coefficients of the IDF model for any county and ARIs of 2 to 100–years along with calculated intensity based on the corresponding IDF model for each ARI based on user-defined duration.

Figure 4.5 is a demonstration of the DDF curves developed based on data taken from NWS-PFDS and non-linearization techniques along with the actual DDF data from NWS-PFDS for Bartow County. This figure shows how the curves fit the DDF data points. To investigate the differences in more detail, Table 4.1 is constructed to show the DDF estimates at discrete values from the two sources. The intensities calculated from developed IDF curves (or EBDUSA source) are within 5% of the intensity values from the original PFDS source.

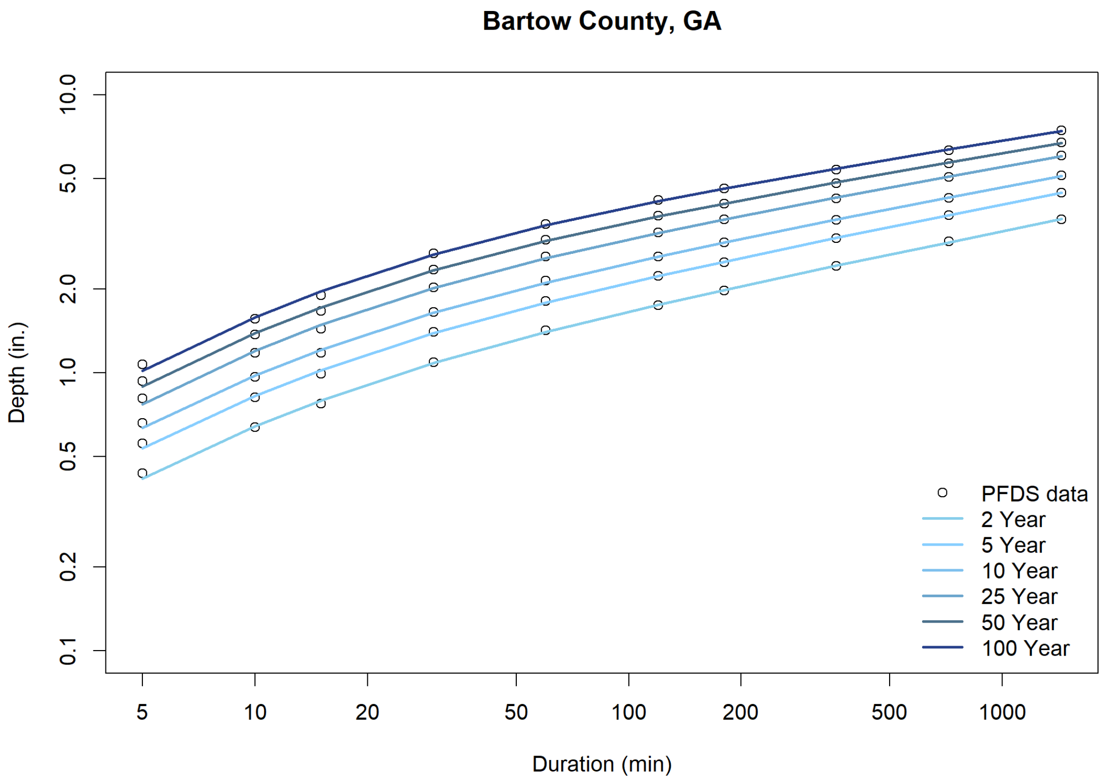
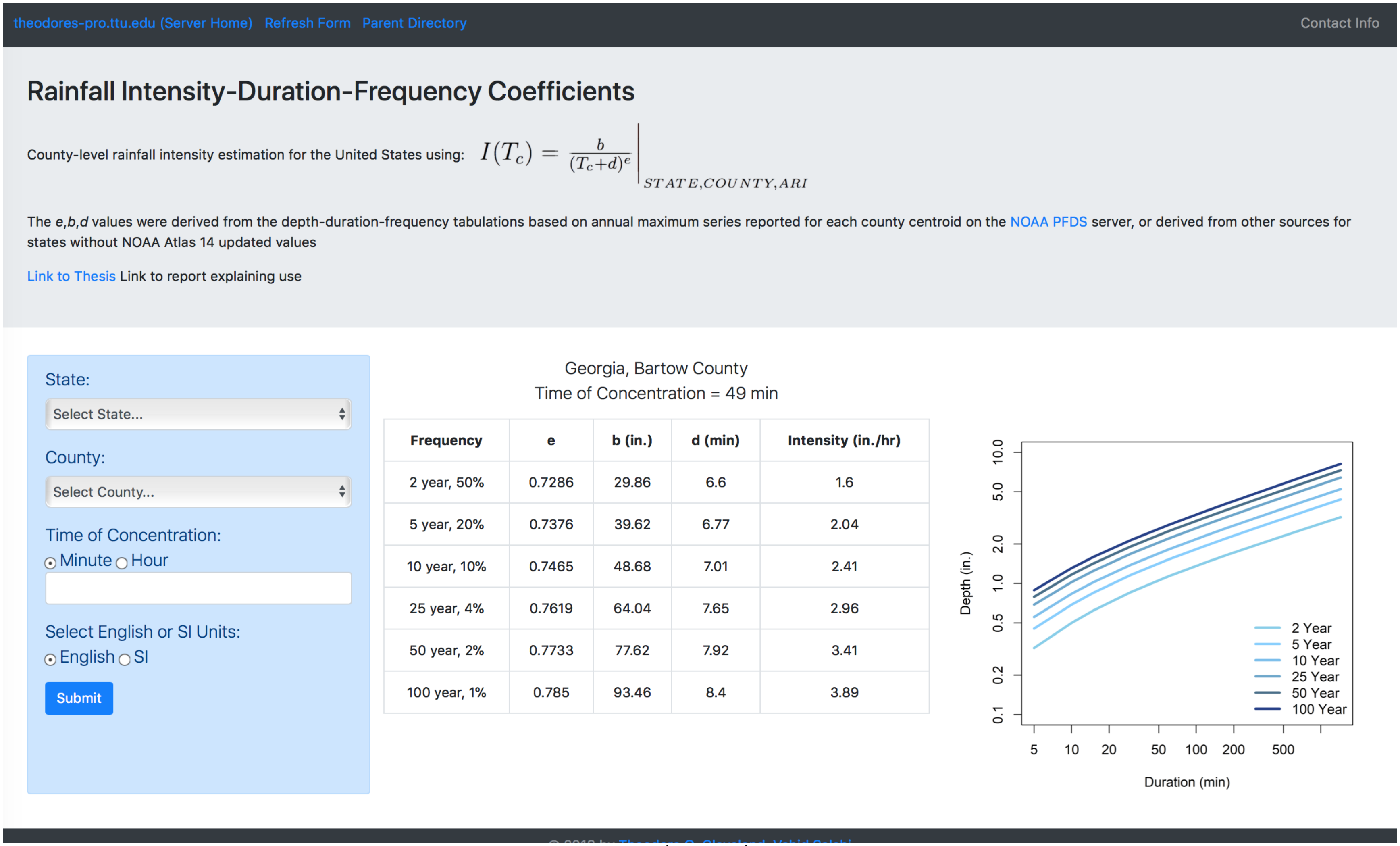


Figure 4.5. Depth-duration by ARI plot for Bartow County, GA.

Continuing with the illustration, an arbitrary duration of 49 minutes was chosen to find the corresponding intensity. The 2-year ARI value of intensity was selected for illustration. First, using EBDUSA, the result was obtained by supplying the state, county, and time of concentration to the EBDUSA program as depicted in Figure 4.6. The 2-year ARI had an intensity value of 1.60 inches per hour.

Table 4.1. Comparison of depth (inches) for Bartow County, GA from PFWS and EBDUSA sources.

		ARI					
Duration	**Source**	2 year	5 year	10 year	25 year	50 year	100 year
5-min	PFDS	0.43	0.55	0.65	0.80	0.93	1.07
	EBDUSA	0.41	0.54	0.63	0.77	0.89	1.02
10-min	PFDS	0.63	0.81	0.97	1.18	1.37	1.56
	EBDUSA	0.64	0.82	0.98	1.19	1.38	1.58
15-min	PFDS	0.78	0.99	1.18	1.44	1.67	1.90
	EBDUSA	0.80	1.02	1.21	1.48	1.72	1.96
30-min	PFDS	1.09	1.40	1.65	2.03	2.35	2.68
	EBDUSA	1.08	1.39	1.65	2.02	2.33	2.67
60-min	PFDS	1.42	1.81	2.14	2.62	3.01	3.43
	EBDUSA	1.40	1.79	2.11	2.56	2.97	3.39
2-hr	PFDS	1.75	2.23	2.62	3.20	3.67	4.17
	EBDUSA	1.76	2.22	2.62	3.18	3.64	4.14
3-hr	PFDS	1.97	2.50	2.94	3.56	4.06	4.59
	EBDUSA	1.98	2.52	2.94	3.57	4.05	4.59
6-hr	PFDS	2.42	3.04	3.54	4.24	4.80	5.38
	EBDUSA	2.40	3.06	3.54	4.26	4.86	5.40
12-hr	PFDS	2.97	3.69	4.26	5.05	5.67	6.31
	EBDUSA	3.00	3.72	4.32	5.04	5.76	6.36
24-hr	PFDS	3.56	4.44	5.12	6.03	6.73	7.44
	EBDUSA	3.60	4.32	5.04	6.00	6.72	7.44



Frequency	e	b (in.)	d (min)	Intensity (in./hr)
2 year, 50%	0.7286	29.86	6.6	1.6
5 year, 20%	0.7376	39.62	6.77	2.04
10 year, 10%	0.7465	48.68	7.01	2.41
25 year, 4%	0.7619	64.04	7.65	2.96
50 year, 2%	0.7733	77.62	7.92	3.41
100 year, 1%	0.785	93.46	8.4	3.89

Figure 4.6. EBDUSA tool for Bartow County, GA for a 49–minute T_C (duration).

Repeating the example using the NWS–PFDS product, we would consult Figure 4.4 to obtain values that bracket 49-minutes in the duration axis for the 2–year ARI. The intensity of 2–year ARI and durations 30–minutes and 60–minutes is 2.19 and 1.42 inches per hour respectively. These intensities and durations can be used to interpolate the intensity of 49–minutes duration.

Ordinary linear interpolation could be performed using a tool like that depicted in Figure 4.7 [6] and would result in Figure 4.8 for ARI of 2–year. The result of intensity using ordinary linear interpolation is 1.70 inches per hour, which is sort of close to what was estimated from EBDUSA (1.60 inches per hour).

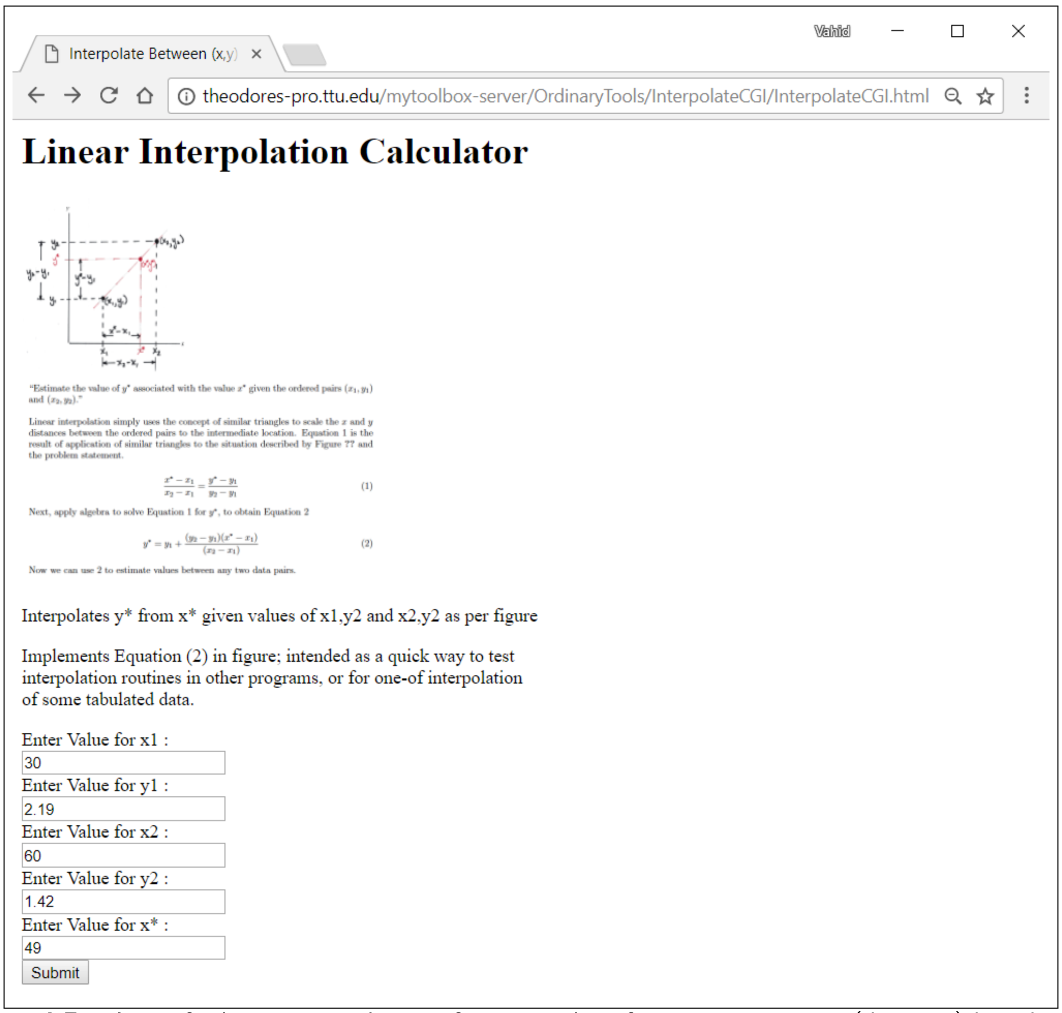


Figure 4.7. Input for linear interpolation of 2–year values for a 49–minute T_C (duration) based on tabulated values from PFDS.

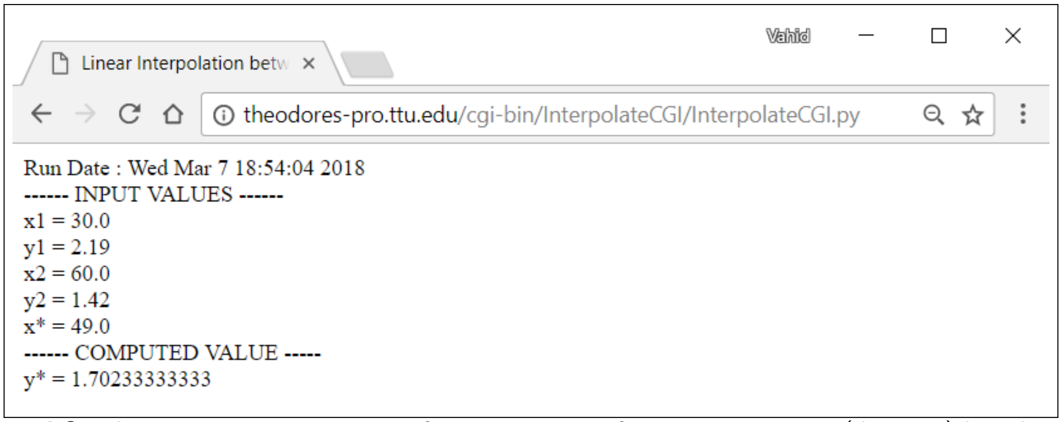


Figure 4.8. Linear interpolation results for 2–year values for a 49–minute T_C (duration) based on tabulated values from PFDS.

A log–log interpolation[1] can be applied using the same tool where the logarithms of durations and intensities are supplied to the tool and the result is inverse-transformed back to the original scale. Figure 4.10 shows the result of log-log interpolation.

The inverse transformed value of intensity is obtained in Equation 4.1 as of 1.61 inches per hour for 2–year ARI which is nearly the same value of EBDUSA tool (1.60 inches per hour).

$$Intensity = 10^{0.2073} = 1.61 \tag{4.1}$$

The same comparison was done for the rest of ARIs and the results of intensity from the three methods are tabulated in Table 4.2. The results obtained from EBDUSA were nearly identical to intensities that the log-log interpolation produced with less than 1% error.

[1]Log-Log Interpolation for this instance is the correct interpolation method to apply to these kind of tabular values [3]. Such interpolation will still use the linear interpolator tool, but on logarithms of the values as shown in Figure 4.9.

Table 4.2. Comparison of intensity (inches/hour) obtained from interpolations and EBDUSA methods for Bartow county, Gorgia for 49–minutes duration. Interpolations are done using intensity values at 30– and 60–minutes durations from NWS-PFDS.

	Linear Interpolation	Log-Log Interpolation	EBDUSA
2-year	1.70	1.61	1.60
5-year	2.17	2.05	2.04
10-year	2.57	2.43	2.41
25-year	3.15	2.97	2.96
50-year	3.63	3.42	3.41
100-year	4.14	3.90	3.89

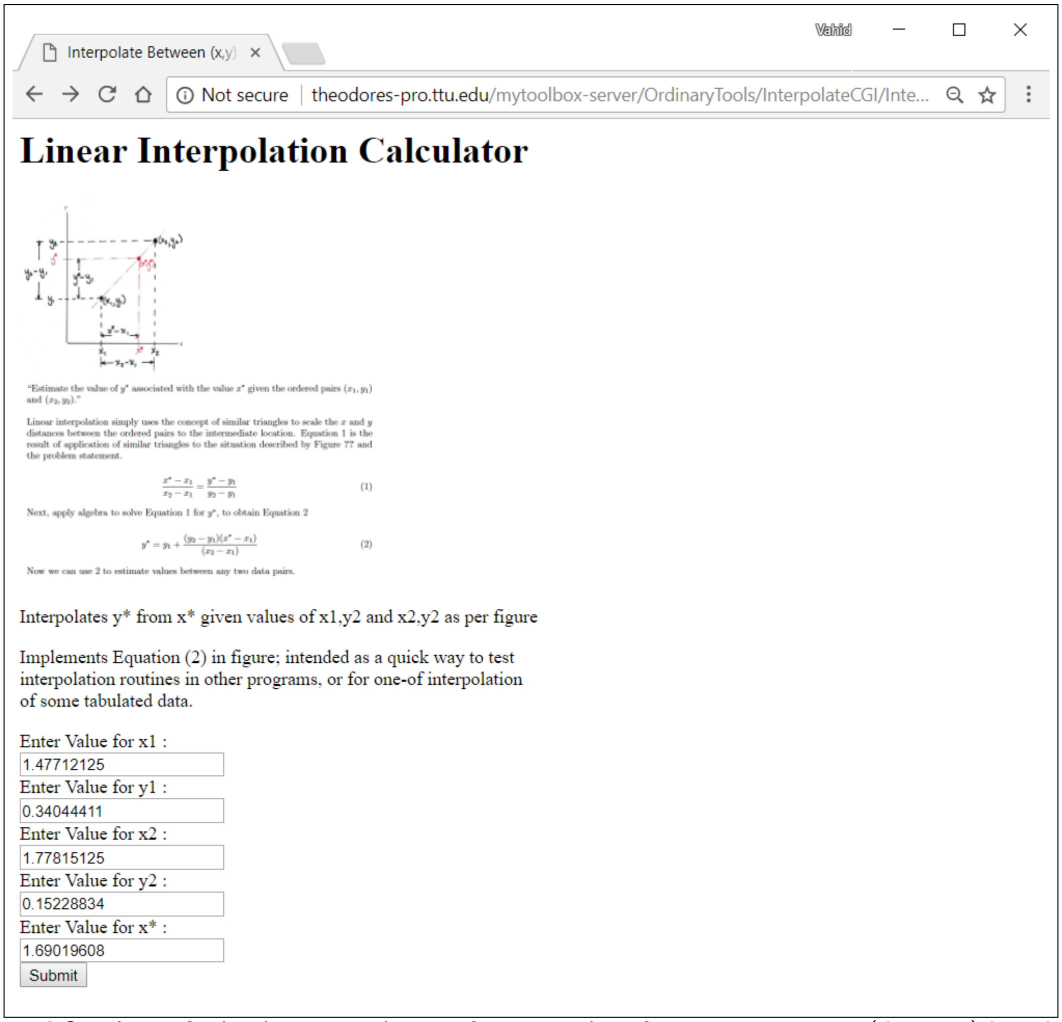


Figure 4.9. Input for log-log interpolation of 2–year values for a 49–minute T_C (duration) based on tabulated values from PFDS. Same interpolation engine, using logarithmic inputs.

Figure 4.10. Log-log interpolation results for 2–year values for a 49–minute T_C (duration) based on tabulated values from PFDS. The result value must be inverse transformed to obtain intensity.

Using EBDUSA tool, several steps were eliminated to get the intensity of durations not listed as discrete values on the products of NWS–PFDS tool.

1. Recording the bracketing values for an intermediate duration between tabulated durations.

2. Computing the logarithms of these values and the associated intensities (or depths).

3. Performing the linear interpolation on the logarithmic values.

4. Inverse-transforming the result back into original units (of intensity or depth).

As mentioned before, EBDUSA database is based on PFDS (NOAA Atlas 14) for all states except Texas. PFDS was missing DDF estimates for Texas; therefore we used the corresponding data for Texas from EBDLKUP-2015.xlsx spreadsheet tool. To show the difference between rainfall depth for Texas against its neighbors and if the rainfall depth varies from Texas to its neighbor gradually and smoothly, depth estimates of 24-hours duration and ARIs of 2– to 100–year of all counties are depicted on US map through Figures 4.11 to 4.16.

The maps of rainfall depth show a general consistency between states' data. Even though the DDF data measurements were done by each state in different time periods and perhaps different measurement tools, there is reasonable consistency between rainfall depth of each state and its neighbors showed in Figures 4.11 to 4.16. However, there are some sharp changes in the rainfall depth in some portion of Texas border that is due to the differences in rainfall data sources of NOAA Atlas 14 (for all the other states) and Texas DDF Atlas 2004 (for Texas). Also, similar maps are made to show the variability of *ebd* coefficients for county-to-county and state-to-state. These maps are documented in Appendix 4.3.

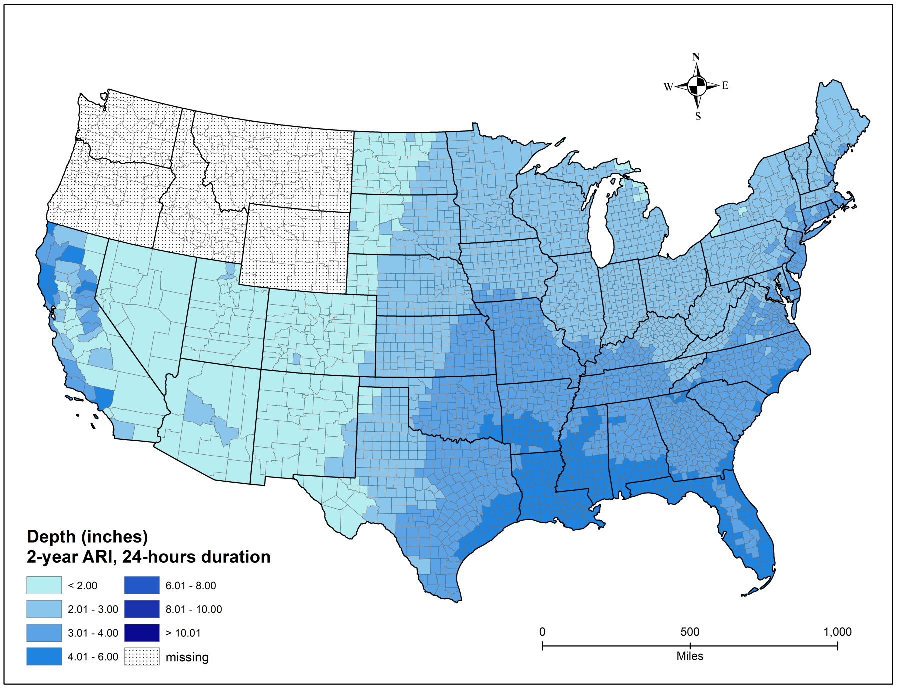


Figure 4.11. Intensity map of 2–year ARI and 24–hours duration.

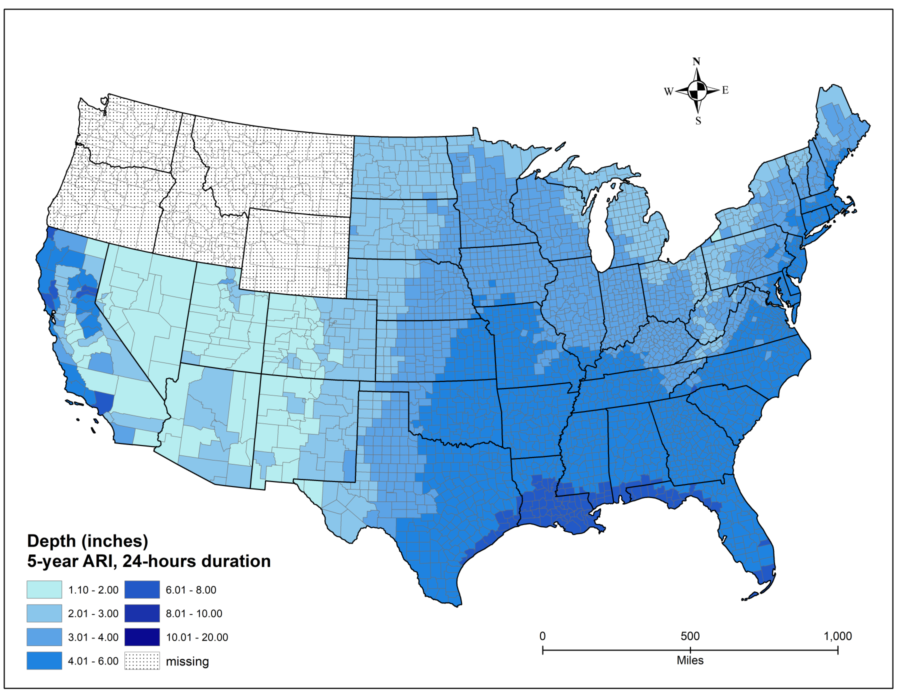


Figure 4.12. Intensity map of 5–year ARI and 24–hours duration.

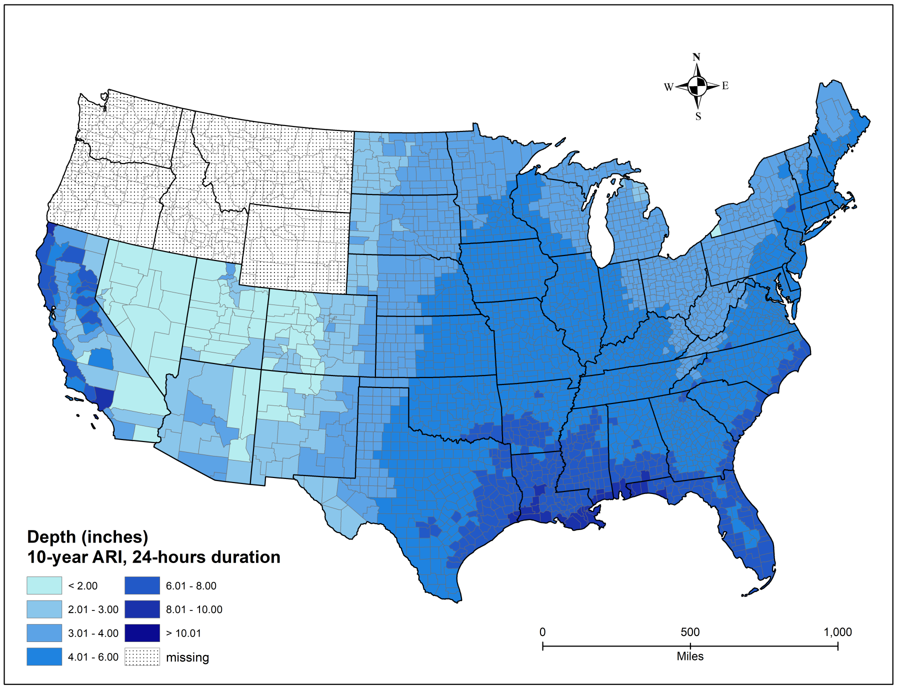


Figure 4.13. Intensity map of 10–year ARI and 24–hours duration.

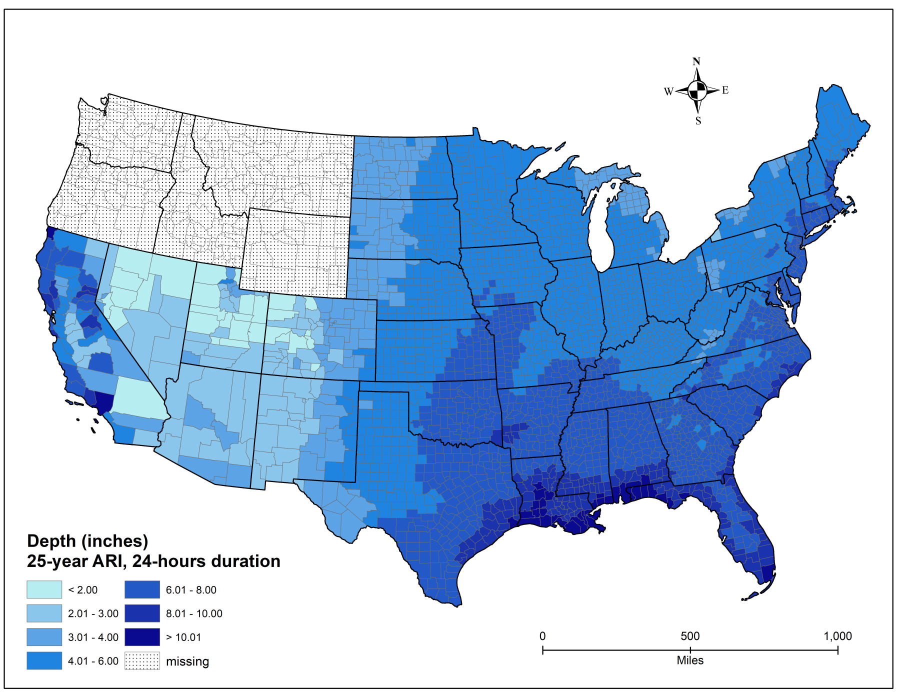


Figure 4.14. Intensity map of 25–year ARI and 24–hours duration.

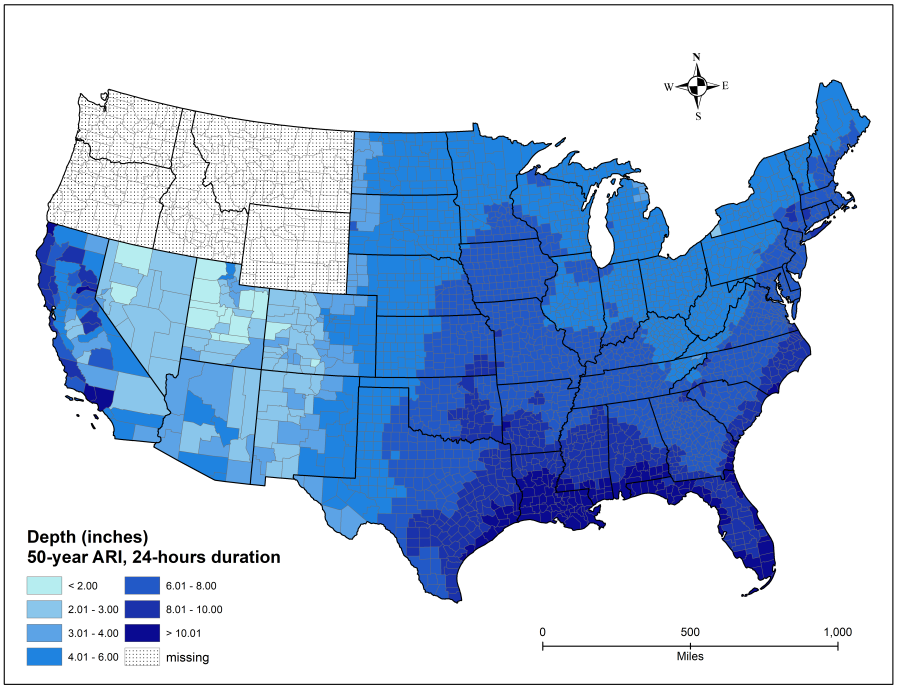


Figure 4.15. Intensity map of 50–year ARI and 24–hours duration.

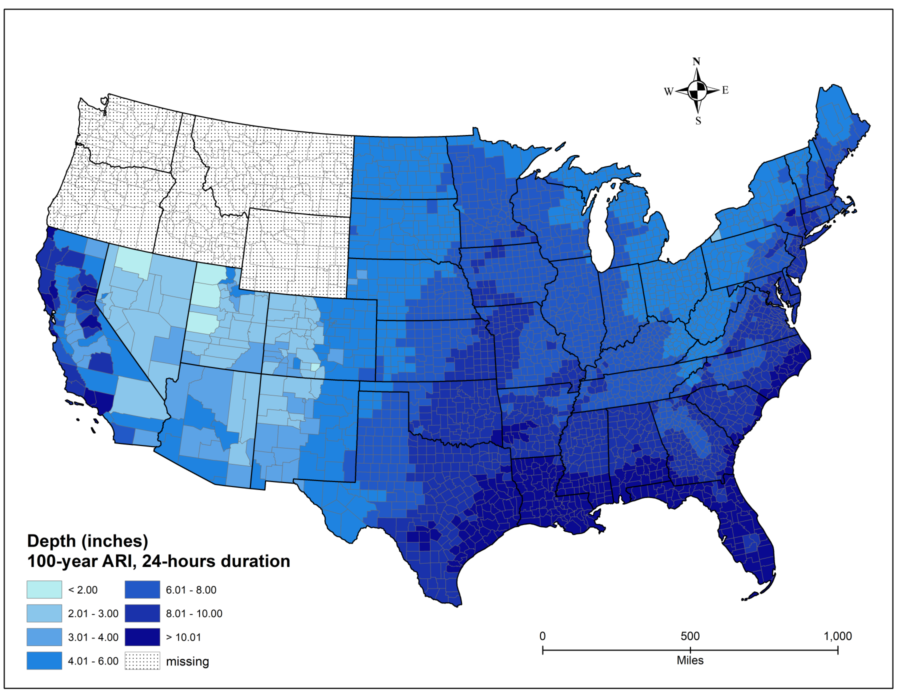


Figure 4.16. Intensity map of 100–year ARI and 24–hours duration.

4.2 Conclusions

The EBDUSA tool was demonstrated to reduce workflow for arbitrary short-duration intensity estimation for rainfall-runoff modeling and related design applications. The tool produces estimates very close to, if not exact in some instances, to estimates obtained directly from the PFDS for the NWS tabulated durations. The tool provides estimates at intermediate durations, between the NWS tabulated values, that are equivalent to log-log interpolation of the NWS tabular values, but with less end-user effort.

The tool is upgradeable by virtue of tracing its database to the NWS-PFDS, as the PFDS updates, the EBDUSA tool can be updated.

4.3 Future Work

Future work is to incorporate the pending NWS upgrade of NOAA Atlas 14 for Texas when it becomes publicly available, and insertion of the data for missing states from their local sources.

Beyond that, the scripts described herein could be modified to perform the calculations in real-time (so that every access consults the NWS server for immediate updates), but should retain a localized database for cases when the NWS server is unavailable (such as during a government shut-down).

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APPENDIX A: *EBD* COEFFICIENTS' MAP

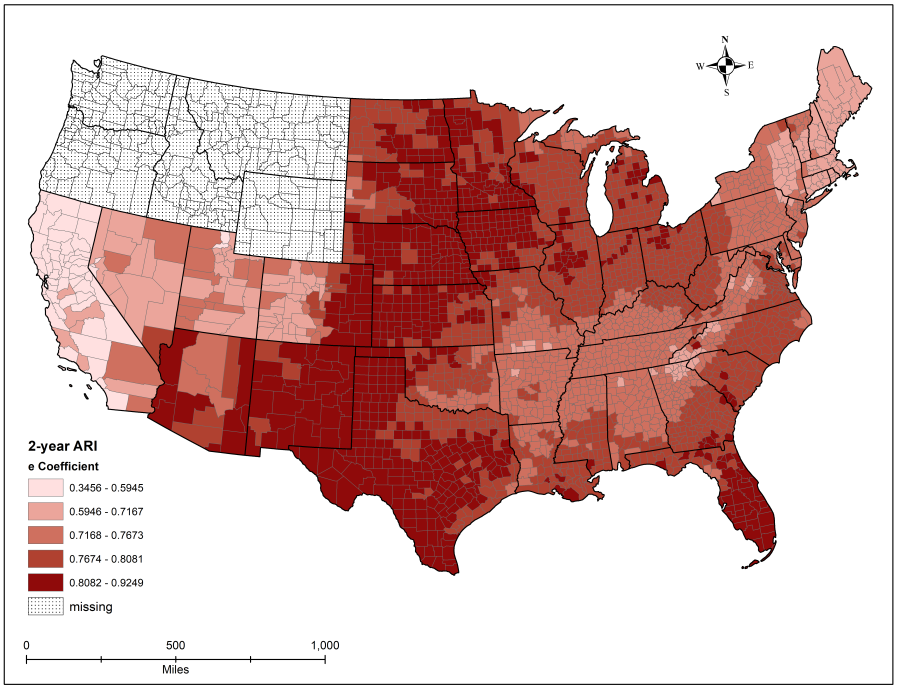

Figure 4.17. US map of e coefficient for 2–year ARI.

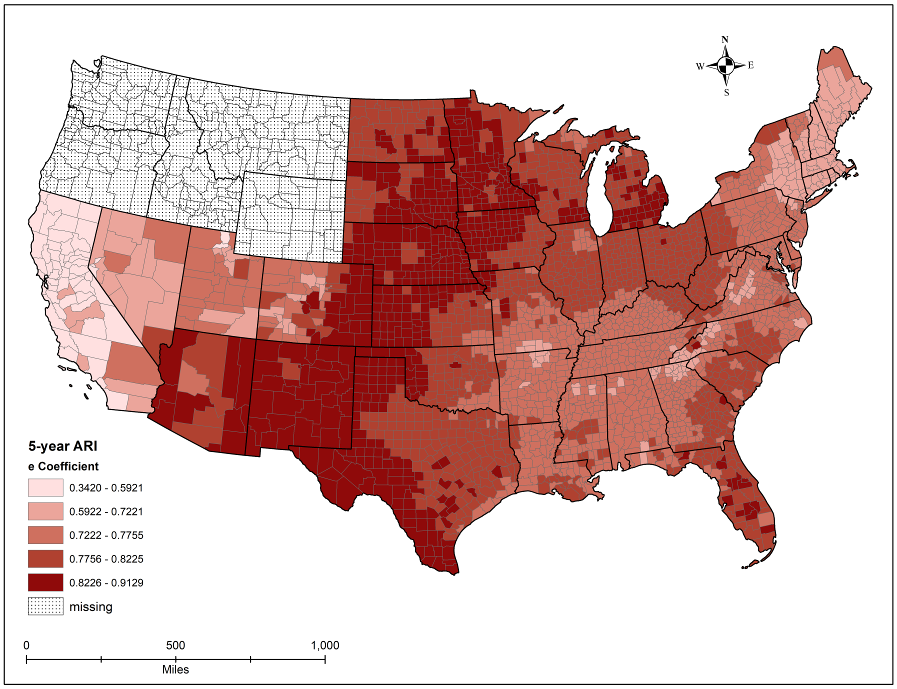

Figure 4.18. US map of *e* coefficient for 5–year ARI.

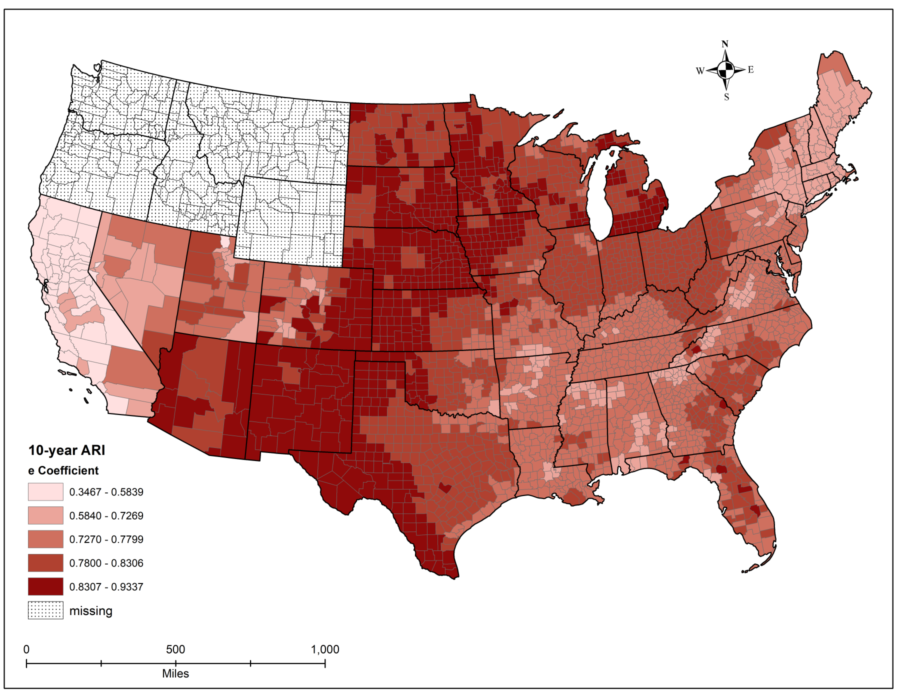

Figure 4.19. US map of *e* coefficient for 10–year ARI.

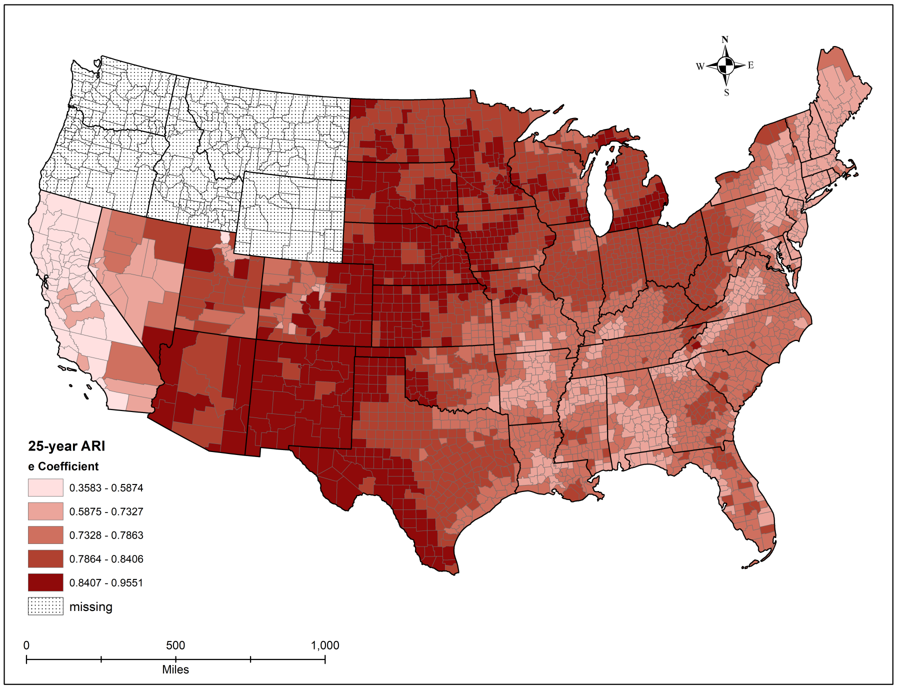

Figure 4.20. US map of *e* coefficient for 25–year ARI.

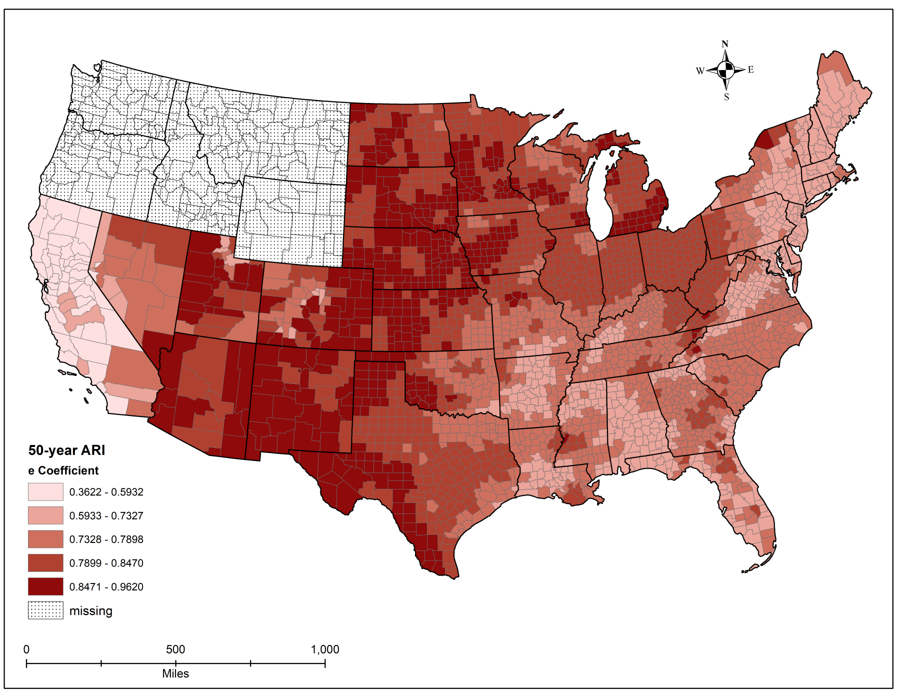

Figure 4.21. US map of *e* coefficient for 50–year ARI.

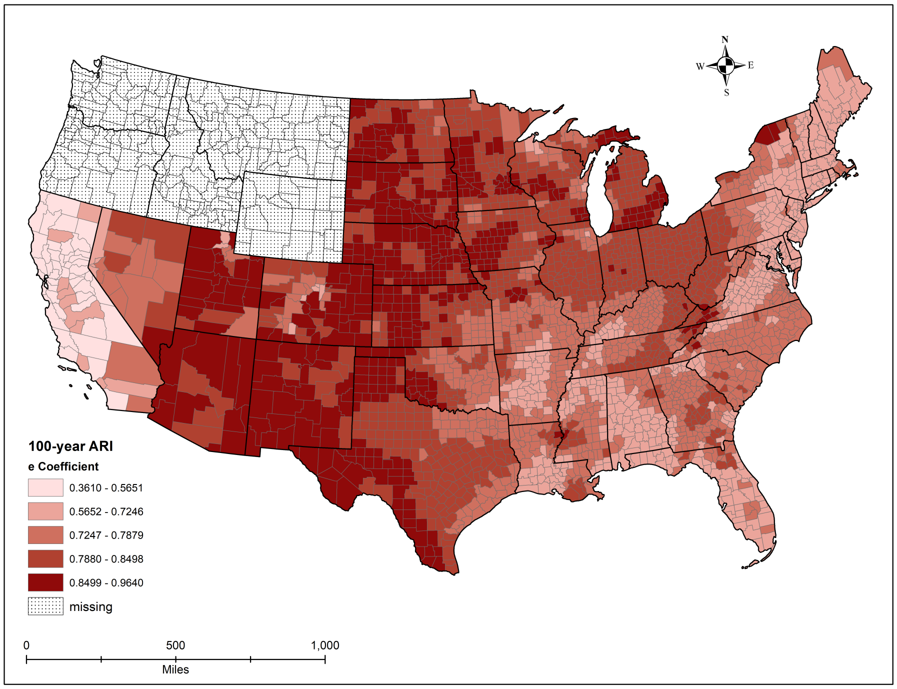

Figure 4.22. US map of *e* coefficient for 100–year ARI.

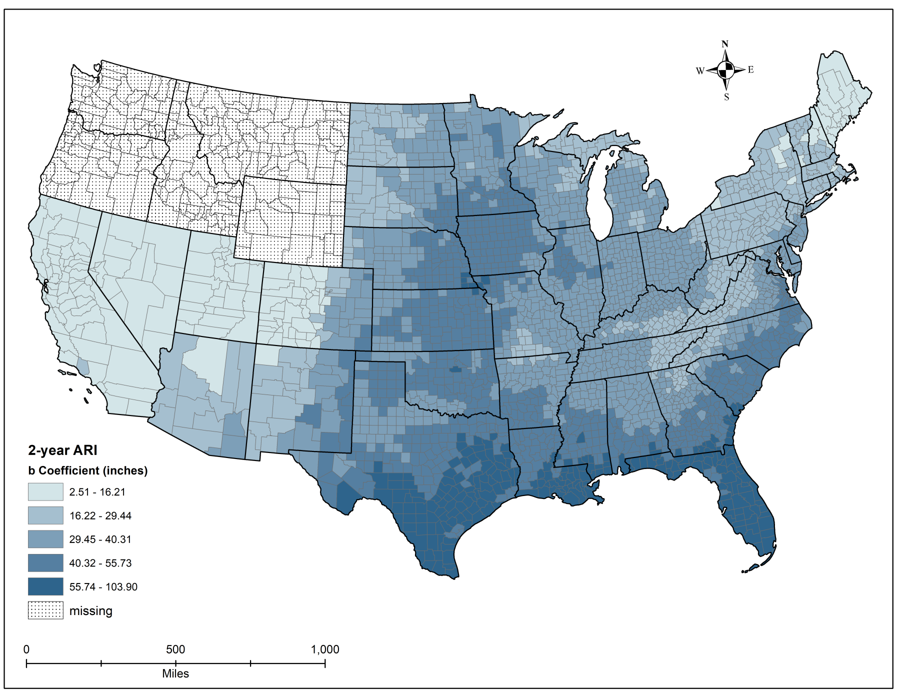

Figure 4.23. US map of *b* coefficient for 2–year ARI.

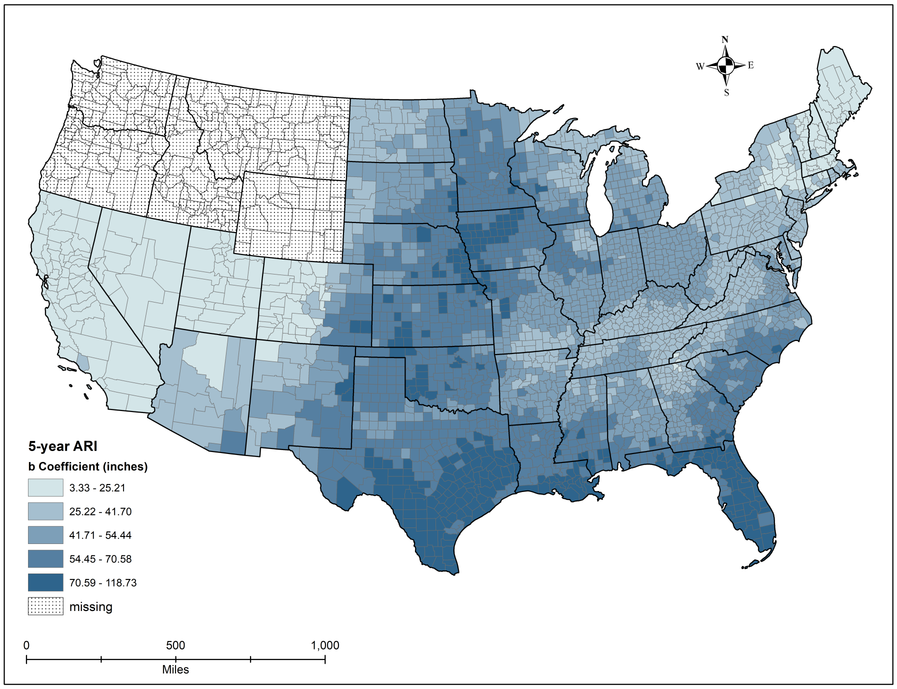

Figure 4.24. US map of *b* coefficient for 5–year ARIp.

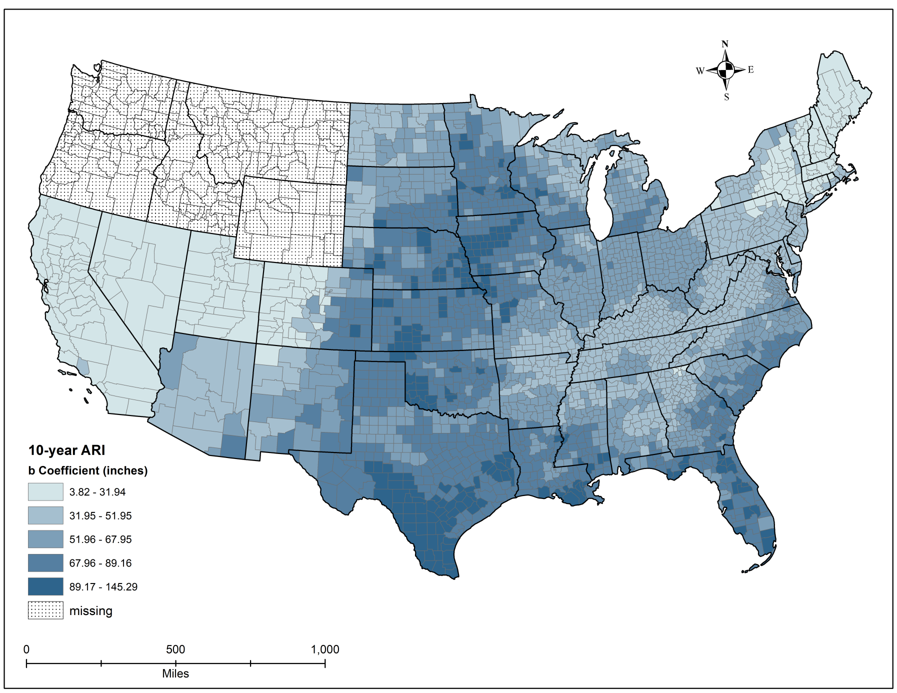

Figure 4.25. US map of *b* coefficient for 10–year ARI.

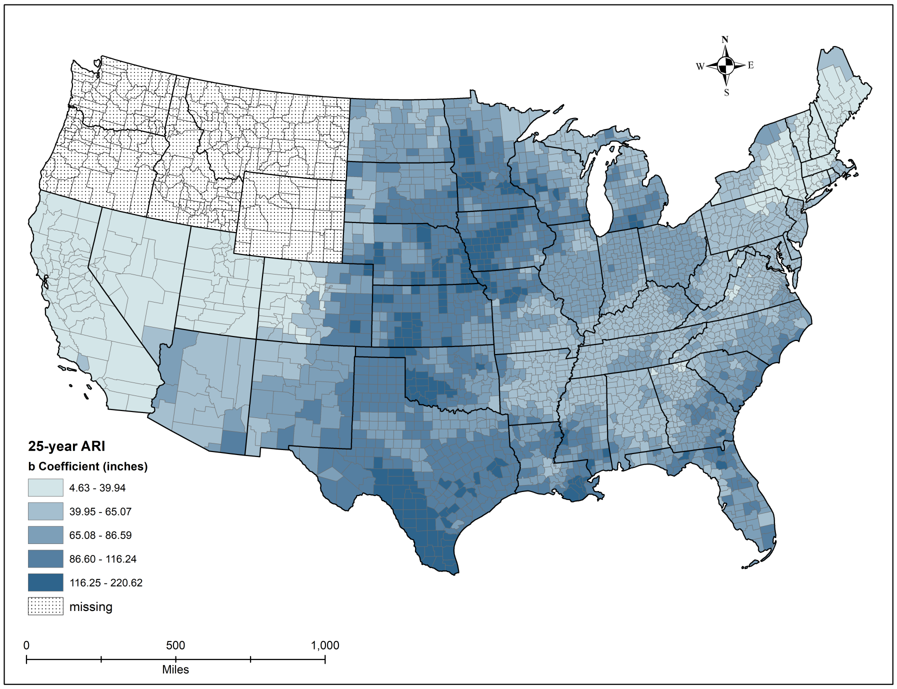

Figure 4.26. US map of *b* coefficient for 25–year ARI.

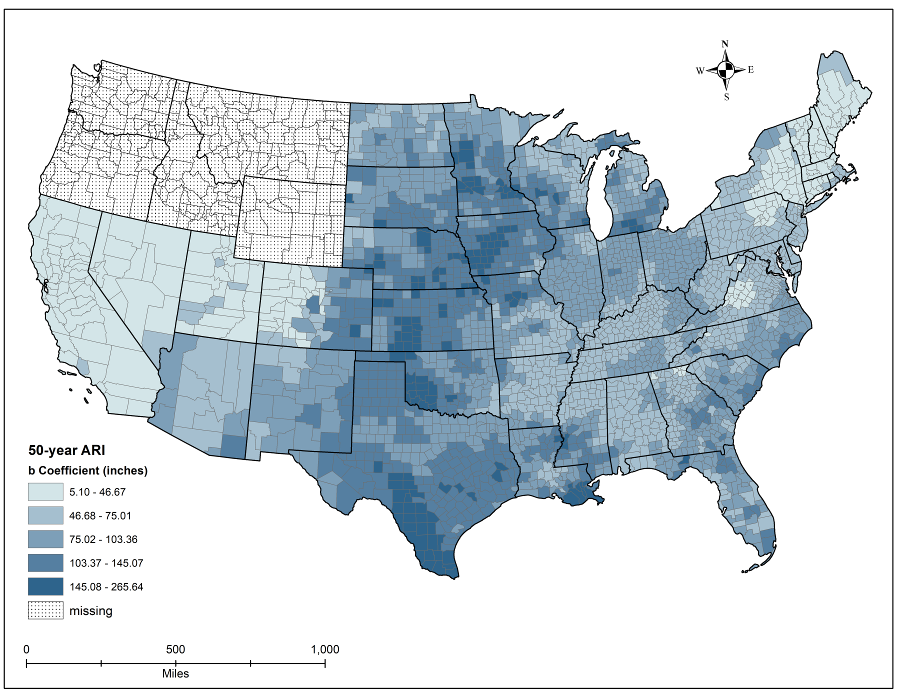

Figure 4.27. US map of *b* coefficient for 50–year ARI.

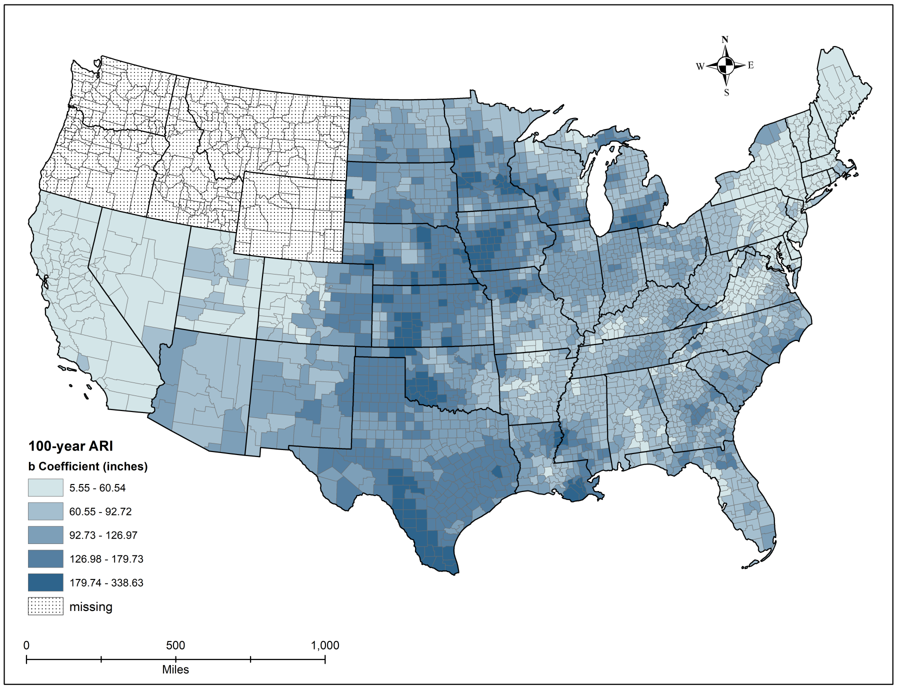

Figure 4.28. US map of *b* coefficient for 100–year ARI.

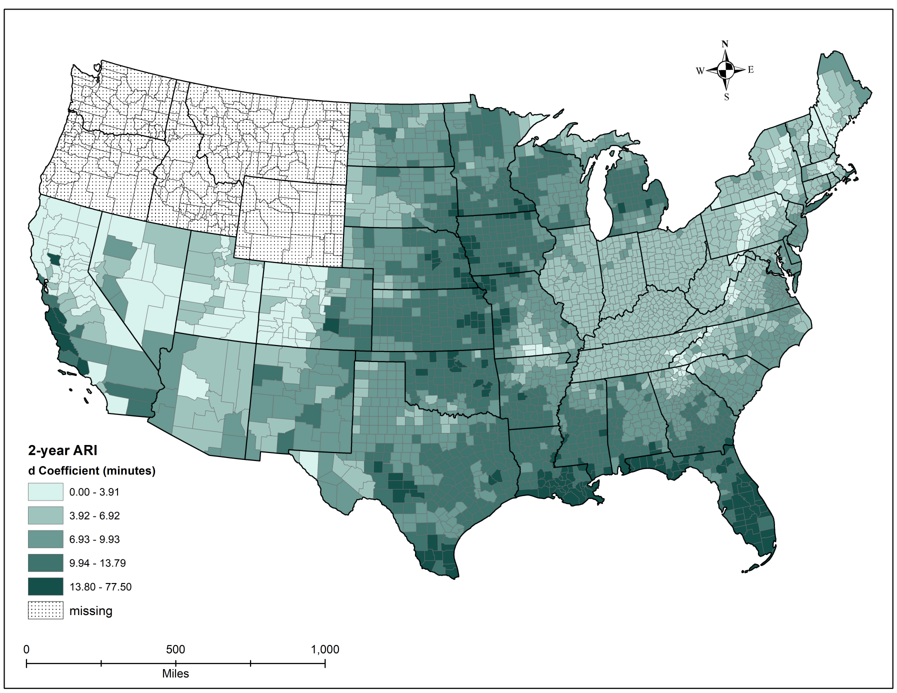

Figure 4.29. US map of *d* coefficient for 2–year ARI.

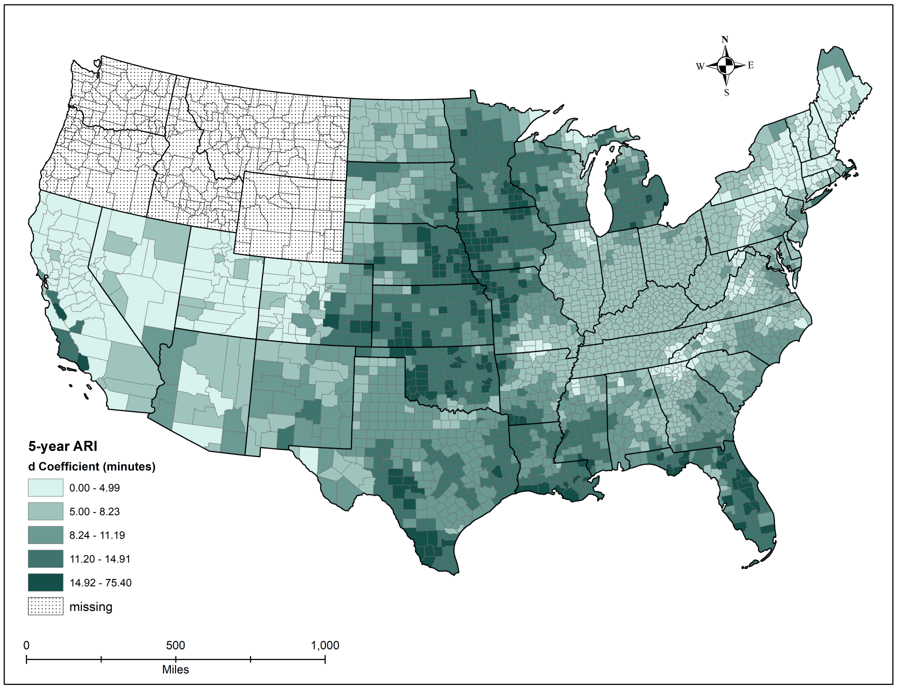

Figure 4.30. US map of d coefficient for 5–year ARI.

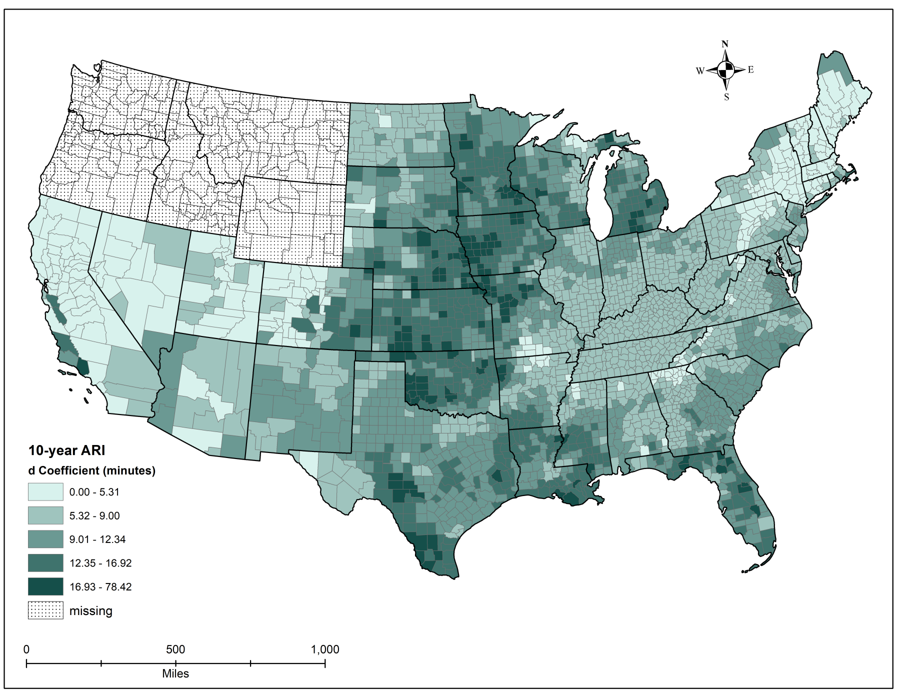

Figure 4.31. US map of d coefficient for 10–year ARI.

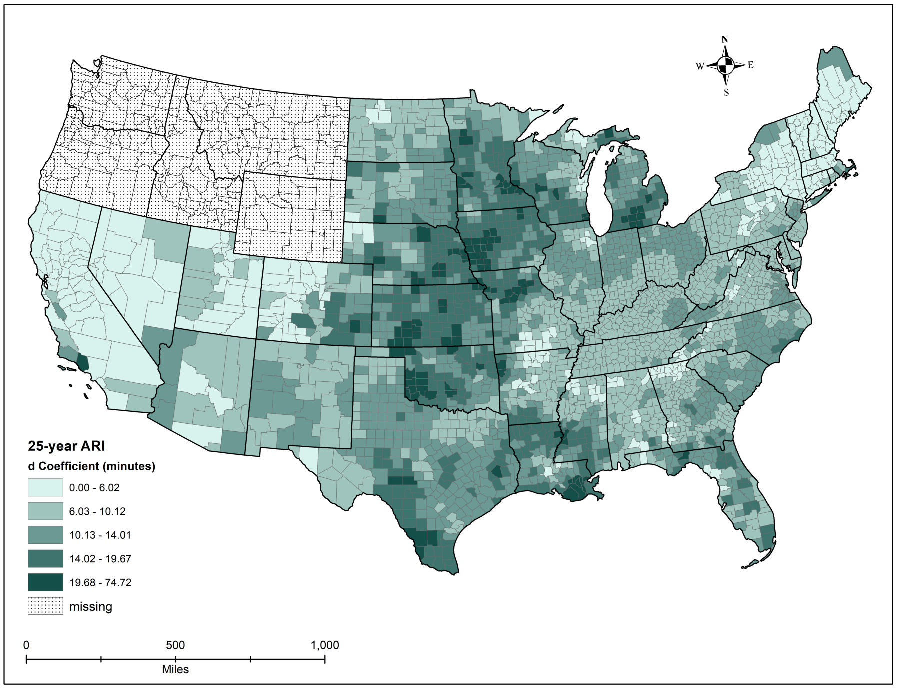

Figure 4.32. US map of d coefficient for 25–year ARI.

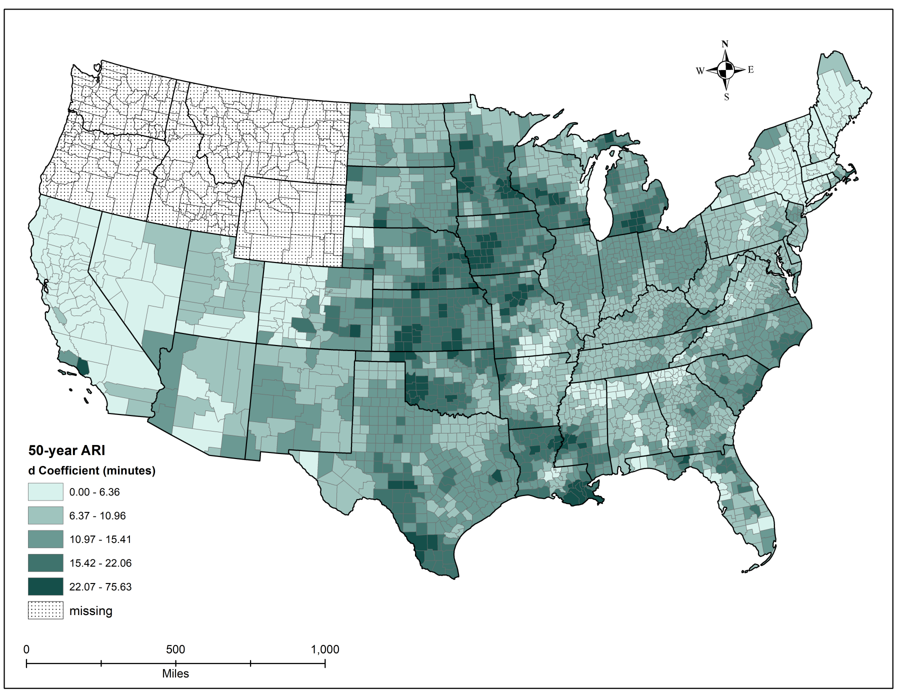

Figure 4.33. US map of d coefficient for 50–year ARI.

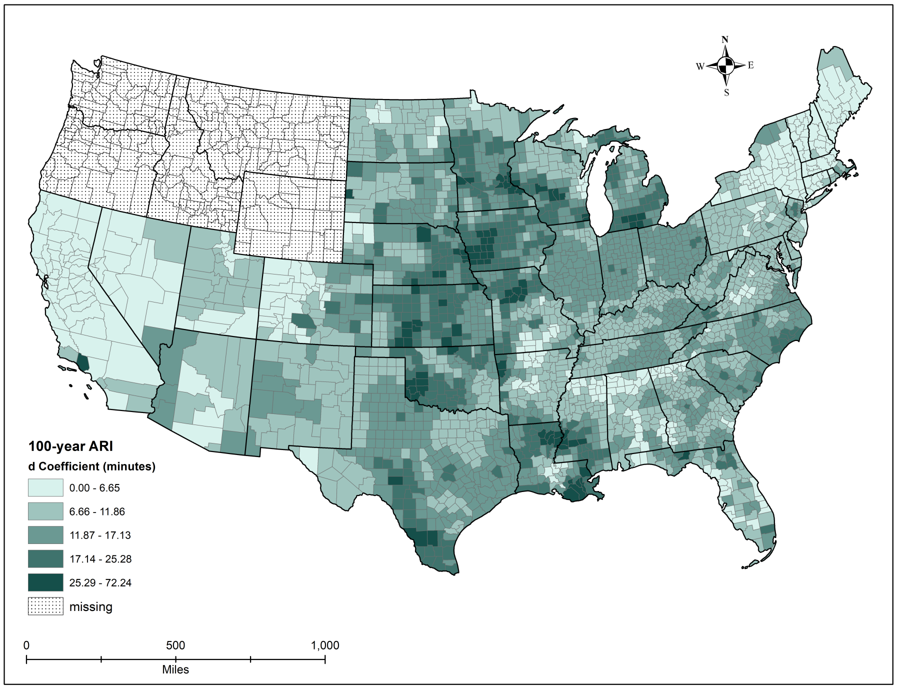

Figure 4.34. US map of d coefficient for 100–year ARI.

APPENDIX B: *EBD* ANALYSIS SCRIPT, THE R SCRIPT OF NON-LINEAR MINIMIZATION (NLM)

Listing 4.1. R code demonstrating.

```
# RCode finds rainfall coefficients for each ARI based on IDF model and nlm package
# Single county
# Adapted from Tay, C. C. 2015. DEVELOPING IDF MODELS USING NONLINEAR MINIMIZATION IN R
#
#### SETUP ####
(WD <- getwd()) #gets working directory
if (!is.null(WD)) setwd(WD) #sets working directory
rm(list = ls()) #removes variables from workspace
#detach(ddf) #preventative measure to detach old excel files
# VERIFY RUNS OK TO HERE 5-SEP-17 TGC
# Assumes THIS script is in same direcory as the input source and target output

##########################
## PROTOTYPE FUNCTIONS ##
##########################
depthfunc <- function(tc,eee,bee,dee) #Depth model - tc is time of concentration in minutes
{
dep <- (tc/60)*(bee/((dee+tc)^eee))
return(dep)
}
##########################
intensityfunc <- function(tc,eee,bee,dee) #Intensity model - tc is ti   me of concentration
     in minutes
{
int <- bee/((dee+tc)^eee) #in/hr
return(int)
}
##########################
sse <- function(x,duration,ddfdepth) #Sum of Errors Squared Function (SSE) used in NLM
    process
{
# x[1] == eee; x[2] == bee; x[3] == dee
sum((ddfdepth - depthfunc(duration,x[1],x[2],x[3]))^2)
}
##########################


#### USER DEFINE DATA #####
# 1. Define "text in quotations.csv" to match source.csv title = Case sensitive
### future version make this interactive so user can enter the filename from console
#ddf <- read.csv("PF_Depth_English_AMS.csv", header = FALSE,na.strings = "")
ddf <- file("PF_Depth_English_AMS.csv", "r") #make connection to input file
metadata <- (readLines(ddf, n=14, ok = TRUE, warn = TRUE,encoding = "unknown", skipNul =
    FALSE))
durfreq <- (readLines(ddf, n=10, ok = TRUE, warn = TRUE,encoding = "unknown", skipNul =
    FALSE))
close(ddf)
# split the string
durfreq <- unlist(strsplit(durfreq,split=","))
# durfreq should be first 10 rows of data
durat <- character(0)
depth2 <- numeric(0)
depth5 <- numeric(0)
depth10 <- numeric(0)
depth25 <- numeric(0)
depth50 <- numeric(0)
depth100 <- numeric(0)
depth200 <- numeric(0)
depth500 <- numeric(0)
depth1000 <- numeric(0)
irow <- -9
for(i in 1:10){
irow <- irow+10
durat[i] <- durfreq[irow] # this is a string array
depth2[i] <- as.numeric(durfreq[irow+1])   # convert to numeric
depth5[i] <- as.numeric(durfreq[irow+2])   # convert to numeric
depth10[i] <- as.numeric(durfreq[irow+3])   # convert to numeric
depth25[i] <- as.numeric(durfreq[irow+4])   # convert to numeric
depth50[i] <- as.numeric(durfreq[irow+5])   # convert to numeric
depth100[i] <- as.numeric(durfreq[irow+6])   # convert to numeric
depth200[i] <- as.numeric(durfreq[irow+7])   # convert to numeric
```

```
depth500[i]  <- as.numeric(durfreq[irow+8])  # convert to numeric
depth1000[i]  <- as.numeric(durfreq[irow+9])  # convert to numeric
}
# Force 10min = 5min values
# first save the 5 min for later plotting
d2temp <-     depth2[1]
d5temp <-     depth5[1]
d10temp <-   depth10[1]
d25temp <-   depth25[1]
d50temp <-   depth50[1]
d100temp <- depth100[1]
#   depth2[1]<-  depth2[2]
#   depth5[1]<-  depth5[2]
#  depth10[1]<- depth10[2]
#  depth25[1]<- depth25[2]
#  depth50[1]<- depth50[2]
# depth100[1]<-depth100[2]
# Minimization Process
duration <- c(5/60,10/60,15/60,30/60,1,2,3,6,12,24)  # durations, numeric in hours
duration <- 60*duration # convert into minutes to work with the prototype functions

# nlm starting guess vector
x <- vector()
x[1] <- 0.004 #eee
x[2] <- 0.004 #bee
x[3] <- 0.004 #dee
NEW <- nlm(sse,c(x[1],x[2],x[3]),duration,depth2,steptol=1e-16, gradtol=1e-6)
ebd2 <- NEW$estimate
depthmodel2 <- depthfunc(duration,ebd2[1],ebd2[2],ebd2[3])
x <- NEW$estimate  #use these values for next ARI
#
NEW <- nlm(sse,c(x[1],x[2],x[3]),duration,depth5,steptol=1e-16, gradtol=1e-6)
ebd5 <- NEW$estimate
depthmodel5 <- depthfunc(duration,ebd5[1],ebd5[2],ebd5[3])
x <- NEW$estimate  #use these values for next ARI
#
NEW <- nlm(sse,c(x[1],x[2],x[3]),duration,depth10,steptol=1e-16, gradtol=1e-6)
ebd10 <- NEW$estimate
depthmodel10 <- depthfunc(duration,ebd10[1],ebd10[2],ebd10[3])
x <- NEW$estimate  #use these values for next ARI
#
NEW <- nlm(sse,c(x[1],x[2],x[3]),duration,depth25,steptol=1e-16, gradtol=1e-6)
ebd25 <- NEW$estimate
depthmodel25 <- depthfunc(duration,ebd25[1],ebd25[2],ebd25[3])
x <- NEW$estimate  #use these values for next ARI
#
NEW <- nlm(sse,c(x[1],x[2],x[3]),duration,depth50,steptol=1e-16, gradtol=1e-6)
ebd50 <- NEW$estimate
depthmodel50 <- depthfunc(duration,ebd50[1],ebd50[2],ebd50[3])
x <- NEW$estimate  #use these values for next ARI
#
NEW <- nlm(sse,c(x[1],x[2],x[3]),duration,depth100,steptol=1e-16, gradtol=1e-6)
ebd100 <- NEW$estimate
depthmodel100 <- depthfunc(duration,ebd100[1],ebd100[2],ebd100[3])

outfile <- file("output.txt","w")
write(c(ebd2[1],ebd2[2],ebd2[3]),outfile,sep=",")
write(c(ebd5[1],ebd5[2],ebd5[3]),outfile,sep=",")
write(c(ebd10[1],ebd10[2],ebd10[3]),outfile,sep=",")
write(c(ebd25[1],ebd25[2],ebd25[3]),outfile,sep=",")
write(c(ebd50[1],ebd50[2],ebd50[3]),outfile,sep=",")
write(c(ebd100[1],ebd100[2],ebd100[3]),outfile,sep=",")
close(outfile)
# plotting for QA/QC checks

# now put the 5 minute values back onto the vectors for plotting
depth2[1] <- d2temp
depth5[1] <- d5temp
depth10[1] <- d10temp
depth25[1] <- d25temp
depth50[1] <- d50temp
depth100[1] <- d100temp

plot(duration,depth100,log="xy",ylim=c(0.1,10),xlab="Duration (min)",ylab="Depth (mm)")
lines(duration,depthmodel100,col="royalblue4", lwd=2)

lines(duration,depth50,type="p")
lines(duration,depthmodel50,col="skyblue4", lwd=2)

lines(duration,depth25,type="p")
```

```
lines(duration,depthmodel25,col="skyblue3", lwd=2)

lines(duration,depth10,type="p")
lines(duration,depthmodel10,col="skyblue2", lwd=2)

lines(duration,depth5,type="p")
lines(duration,depthmodel5,col="skyblue1", lwd=2)

lines(duration,depth2,type="p")
lines(duration,depthmodel2,col="skyblue", lwd=2)

leg <- c("2 Year", "5 Year","10 Year","25 Year","50 Year","100 Year")
legend("bottomright", leg , col=c("skyblue","skyblue1","skyblue2","skyblue3","skyblue4","
    royalblue4"), lwd=2, bty="n")
```

APPENDIX C: EBDUSA WEB APPLICATION PROGRAM SCRIPTS

Listing 4.2. PHP code as configuration.php file to connect to MySQL data Server.

```
<?Php
/// Update database login details here ///
$dbhost_name = "host_name";         // host name
$database = "database_name";        // database name
$username = "username";             // login userid
$password = "password";             // password
/// End of database details of the server ///

/// Database connection function - no need to edit below ///
try {
$dbo = new PDO('mysql:host='.$dbhost_name.';dbname='.$database, $username, $password);
} catch (PDOException $e) {
print "Error!: " . $e->getMessage() . "<br/>";
die();
}
?>
```

Listing 4.3. Web application HTML and PHP code as index.php file.

```
<?php
//// Database connection
require 'config.php';
//// End of connecting to database
?>

<!DOCTYPE html>
<html>
<head>
<title>EBD Look Up</title>
<!-- Bootstrap core CSS -->
<link rel="stylesheet" href="https://maxcdn.bootstrapcdn.com/bootstrap/4.0.0-beta.3/css/
     bootstrap.min.css" integrity="sha384-Zug+QiDoJOrZ5t4lssLdxGhVrurbmBWopoEl+
     M6BdEfwnCJZtKxi1KgxUyJq13dy" crossorigin="anonymous">
<!-- Custom styles -->
<link href="custom.css" rel="stylesheet">

<SCRIPT language=JavaScript>
function reload(form){
var val=form.cat.options[form.cat.options.selectedIndex].value;
self.location='index.php?cat=' + val ;
}
</script>
</head>

<body>
<nav class="navbar navbar-expand-lg navbar-dark bg-dark">
<!-- <a class="navbar-brand" href="#">Navbar</a> -->
<button class="navbar-toggler" type="button" data-toggle="collapse" data-target="#
     navbarSupportedContent" aria-controls="navbarSupportedContent" aria-expanded="false"
     aria-label="Toggle navigation">
<span class="navbar-toggler-icon"></span>
</button>

<div class="collapse navbar-collapse" id="navbarSupportedContent">
<ul class="navbar-nav mr-auto">
<li class="nav-item active">
<a class="nav-link" href="index.php">Home <span class="sr-only">(current)</span></a>
</li>
</ul>
<ul class="navbar-nav ml-auto">
<li class="nav-item">
<a class="nav-link" href="contact.php">Contact Info <span class="sr-only">(current)</span
     ></a>
</li>
</ul>
</div>
</nav>
<!-- Main jumbotron for call to action -->
<div class="jumbotron">
```

```
<h2 class="display-6">Rainfall Intensity-Duration-Frequency Coefficients</h2>
<p>County-level rainfall intensity estimation for the United States </p>
</div>


<!-- PHP code to construct the drop-down list -->
<?Php

@$cat=$_GET['cat']; // Use this line or below line if register_global is off
if(strlen($cat) < 0 ){ // to check if $cat is numeric data or not.
echo "Data Error";
exit;
}

//// Getting the data from Mysql table for first list box; States
$quer2="SELECT DISTINCT State FROM ebdval";
//// End of query for first list box

//// for second drop down list, Counties, check if $cat is selected else display all the
     $subcat
//// $cat --> Category --> States
//// $subcat --> subcategory --> Counties
if(isset($cat) and strlen($cat) > 0){
$quer="SELECT DISTINCT County FROM ebdval where State='".$cat."'";
}else{$quer="SELECT DISTINCT County FROM ebdval"; }
//// end of query for second subcategory drop down list box

echo "<div class='container-fluid'>";
echo "<div class='row pad-32'>";
//// First Column - the input forms
echo "<div class='col-md-3 col-sm-12 alert alert-primary'>";
echo "<form method=post name=f1 action='index.php'>";

//// Starting of first drop downlist
echo " <div class='form-group'><label class='lead' for='cat'>State:</label>";
echo "<select class='form-control' name='cat' onchange=\"reload(this.form)\" required><
     option value=''>Select State...</option>";
foreach ($dbo->query($quer2) as $i) {
if($i['State']==@$cat){echo "<option selected value='$i[State]'>$i[State]</option>"."<BR
     >";}
else {echo  "<option value='$i[State]'>$i[State]</option>";
}
}
echo "</select></div>";
//// end of the first drop down list

//// Starting of second drop downlist
echo "<div class='form-group'><label class='lead' for='subcat'>County:</label>";
echo "<select class='form-control' name='subcat' required><option value=''>Select County
     ...</option>";
foreach ($dbo->query($quer) as $j) {
echo  "<option value='$j[County]'>$j[County]</option>";
}
echo "</select></div>";
//// end of the second drop down list

//// Time of Concentration input box
echo "<p class='lead'>Time of Concentration:<br>";
echo "<input type='radio' name='T' value='min' checked> Minute  ";
echo "<input type='radio' name='T' value='hr'> Hour";
echo "<input type='text' name='toc' class='form-control' id='toc' pattern='[+-]?([0-9]*[.])
     ?[0-9]+' title='input a number' required></p>  ";
//// end of Time of Concentration input box

//// Unit radio check box
echo "<p class='lead'>Select English or SI Units:<br>";
echo "<input type='radio' name='unit' value='eng' checked> English  ";
echo "<input type='radio' name='unit' value='si'> SI</p>";
//// end of Unit radio check box

//// submit button
echo "<input type=submit class='btn btn-primary' value=Submit>";
//// end of submit button

echo "</form>";
echo "</div>";

if ( isset($_POST['cat']) && isset($_POST['subcat']) && isset($_POST['toc'])) {
//// Second Column - the table of ebd values
echo "<div class='col-md-5 col-sm-12'>";
```

```
echo "<p class='lead text-center'>".$_POST['cat'].", ".$_POST['subcat']."<br>";
$state="'".$_POST['cat']."'";
$county="'".$_POST['subcat']."'";
if ($_POST['T']==='min') {
$time = $_POST['toc'];
echo "Time of Concentration = ".$_POST['toc']." min</p>";
} else {
$time = $_POST['toc']*60;
echo "Time of Concentration = ".$_POST['toc']." hr </p>";
}
$tex = "SELECT * FROM ebdval WHERE State=".$state." AND County=".$county;
$stmt = $dbo->query($tex);

//// $rinput a string variable which will have all the R inputs parameters together
     seperated with comma
$rinput = "";
//// crate table of ebd outputs:
echo "<table class='table table-bordered text-center'>"."\n";
echo "<tr><th scope='col'>";
echo "Frequency";
echo "</th><th scope='col'>";
echo "e";
echo "</th><th scope='col'>";
if ($_POST['unit']==='si') {
echo "b (mm)";
} else {
echo "b (in.)";
}
echo "</th><th scope='col'>";
echo "d (min)";
echo "</th><th scope='col'>";
if ($_POST['unit']==='si') {
echo "Intensity (mm/hr)";
} else {
echo "Intensity (in./hr)";
}
while ( $row = $stmt->fetch(PDO::FETCH_ASSOC) ) {
echo "</th><tr><td>";
echo $row['ARI']." year, ". 100/round($row['ARI']+0,4)."%";
echo "</td><td>";
echo round($row['e']+0,4);
$rinput =$rinput.round($row['e']+0,4).",";
echo "</td><td>";
if ($_POST['unit']==='si') {
$b=$row['b']*25.4;
} else {
$b=$row['b'];
}
echo round($b,2);
$rinput =$rinput.round($b,2).",";
echo "</td><td>";
echo round($row['d']+0,2);
$rinput =$rinput.round($row['d']+0,2).",";
echo "</td><td>";
$inten = ($b+0)/($time+$row['d']+0)**($row['e']+0);
echo round($inten,2);
echo "</td></tr>\n";
}
echo "</table>\n";
//// concatenate the units ro R input $rinput
$rinput = $rinput.$_POST['unit'];
echo "</div>";

//// Third Column - plot ////
echo "<div class='col-md-4 col-sm-12'><br>";

// execute R script from shell
// this will save a plot at temp.png to the filesystem
$exec_arg='"C:\Program Files\R\R-3.3.2\bin\Rscript" '."my_rscript.R ".$rinput;
exec($exec_arg);

// return image tag
$nocache = rand();
echo "<div>";
echo "<img class='img-fluid' width='100%' src='temp.png'>";
echo "</div>";

echo "</div>";
}
```

```
echo "</div>";
echo "</div>";
?>

<br>
<!--Footer-->
<footer class="footer">
<div class="navbar navbar-dark bg-dark justify-content-center">
<p class="text-muted credit">&copy 2018 by <a href="http://www.rtfmps.com" target="_blank">
     Theodore G. Cleveland</a>,
<a href="http://myweb.ttu.edu/vsalahia" target="_blank">Vahid Salahi</a></p>
</div>
</footer>

<!-- Bootstrap core JavaScript
================================================== -->
<!-- Placed at the end of the document so the pages load faster -->
<!-- jquery link -->
<script src="https://code.jquery.com/jquery-3.2.1.slim.min.js" integrity="sha384-
     KJ3o2DKtIkvYIK3UENzmM7KCkRr/rE9/Qpg6aAZGJwFDMVNA/GpGFF93hXpG5KkN" crossorigin="
     anonymous"></script>
<!-- <script>window.jQuery || document.write('<script src="../../../../assets/js/vendor/
     jquery-slim.min.js"><\/script>')</script>
<script src="Boostrap/assets/js/vendor/popper.min.js"></script> -->
<!-- javascript for bootstrap -->
<script src="https://maxcdn.bootstrapcdn.com/bootstrap/4.0.0-beta.3/js/bootstrap.min.js"
     integrity="sha384-a5N7Y/aK3qNeh15eJKGWxsqtnX/wWdSZSKp+81YjTmS15nvnvxKHuzaWwXHDli+4"
     crossorigin="anonymous"></script>
</body>

</html>
```

Listing 4.4. my-plot.R code used as a web applicationt server to generate the log-log plot of depth-duration by ARI.

```
args <- commandArgs(TRUE)
ebd <- strsplit(args,",")

n<-1
val <- c()
for (i in 1:18){
        val[n] <- as.numeric(ebd[[1]][n])
        n <- n+1
}
depthfunc <- function(tc,eee,bee,dee) #Depth model - tc is time of concentration in minutes
{
        dep <- (tc/60)*(bee/((dee+tc)^eee))
        return(dep)
}
unit <- ebd[[1]][19]
duration <- c(5/60,10/60,15/60,30/60,1,2,3,6,12,24)  # durations, numeric in hours
duration <- 60*duration # convert into minutes to work with the prototype functions
depthmodel2 <- depthfunc(duration,val[1],val[2],val[3])
depthmodel5 <- depthfunc(duration,val[4],val[5],val[6])
depthmodel10 <- depthfunc(duration,val[7],val[8],val[9])
depthmodel25 <- depthfunc(duration,val[10],val[11],val[12])
depthmodel50 <- depthfunc(duration,val[13],val[14],val[15])
depthmodel100 <- depthfunc(duration,val[16],val[17],val[18])

if (unit=='si'){
        png(filename="temp.png",height = 1600, width = 1600, res=300)
        plot(duration,depthmodel2,log="xy",ylim=c(2.54,254),type='l',col="skyblue", lwd=3,
            xlab="Duration (min)",ylab="Depth (mm)")
        lines(duration,depthmodel5,col="skyblue1", lwd=3)
        lines(duration,depthmodel10,col="skyblue2", lwd=3)
        lines(duration,depthmodel25,col="skyblue3", lwd=3)
        lines(duration,depthmodel50,col="skyblue4", lwd=3)
        lines(duration,depthmodel100,col="royalblue4", lwd=3)
        leg <- c("2 Year", "5 Year","10 Year","25 Year","50 Year","100 Year")
        legend("bottomright", leg , col=c("skyblue","skyblue1","skyblue2","skyblue3","
            skyblue4","royalblue4"), lwd=3, bty="n")
        dev.off()
} else{
        png(filename="temp.png" ,height = 3200, width = 3200, res=600)
        plot(duration,depthmodel2,log="xy",ylim=c(0.1,10),type='l',col="skyblue", lwd=3,
            xlab="Duration (min)",ylab="Depth (in.)")
        lines(duration,depthmodel5,col="skyblue1", lwd=3)
        lines(duration,depthmodel10,col="skyblue2", lwd=3)
        lines(duration,depthmodel25,col="skyblue3", lwd=3)
```

```
        lines(duration,depthmodel50,col="skyblue4", lwd=3)
        lines(duration,depthmodel100,col="royalblue4", lwd=3)
        leg <- c("2 Year", "5 Year","10 Year","25 Year","50 Year","100 Year")
        legend("bottomright", leg , col=c("skyblue","skyblue1","skyblue2","skyblue3","
            skyblue4","royalblue4"), lwd=3, bty="n")
        dev.off()
}
```