Research Report
KTC-00-18/SPR-178-98

Kentucky Transportation Center

College of Engineering

REVISION OF THE RAINFALL INTENSITY DURATION CURVES FOR THE COMMONWEALTH OF KENTUCKY

UNIVERSITY OF KENTUCKY

UNIVERSITY OF KENTUCKY

College of Engineering

Kentucky Transportation Center

Our Mission

We provide services to the transportation community
through research, technology transfer and education.
We create and participate in partnerships to promote
safe and effective transportation systems.

We Value...

Teamwork -- Listening and Communicating, Along with Courtesy and Respect for Others
Honesty and Ethical Behavior
Delivering the Highest Quality Products and Services
Continuous Improvement in All That We Do

For more information or a complete publication list, contact us

KENTUCKY TRANSPORTATION CENTER

176 Raymond Building
University of Kentucky
Lexington, Kentucky 40506-0281

(859) 257-4513
(859) 257-1815 (FAX)
1-800-432-0719
www.ktc.uky.edu
ktc@engr.uky.edu

Research Report
KTC-00-18

REVISION OF THE RAINFALL-INTENSITY DURATION CURVES FOR THE COMMONWEALTH OF KENTUCKY

By

Bernadette S. Dupont
Transportation Engineer II

and

David L. Allen
Transportation Engineer V

Kentucky Transportation Center
College of Engineering
University of Kentucky
Lexington, Kentucky

In cooperation with

Kentucky Transportation Cabinet
Commonwealth of Kentucky

and

The Federal Highway Administration
U.S. Department of Transportation

March 2000

<table>
<tr><td>1. Report No.
KTC-00-18</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Revision of the Rainfall Intensity Duration Curves for the Commonwealth of Kentucky</td><td colspan="2">5. Report Date
June, 1999</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s):
Bernadette Dupont and David Allen</td><td colspan="2">8. Performing Organization Report No.
KTC-00-18</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Kentucky Transportation Center
College of Engineering
University of Kentucky
Lexington, KY 40506-0043</td><td colspan="2">10. Work Unit No. (TRAIS)</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
KYSPR 98-178</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
Kentucky Transportation Cabinet
State Office Building
Frankfort, KY 40622</td><td colspan="2">13. Type of Report and Period Covered
Final</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code</td></tr>
<tr><td colspan="4">15. Supplementary Notes
Prepared in cooperation with the Federal Highway Administration, U.S. Department of Transportation. Study Title: Revision of the Rainfall Intensity Duration Curves for the Commonwealth of Kentucky.</td></tr>
<tr><td colspan="4">16. Abstract
The purpose of this study was to revise and update the existing Rainfall Intensity-Duration-Frequency (IDF) Curves for the Commonwealth of Kentucky. The nine curves that currently govern Kentucky are based on data from First-Order Weather Stations in and around Kentucky. However, the new curves only utilize data from within the State. The data was gathered from both First Order and Co-operative Weather Stations. In accordance with Bulletin 71, the new curves reflect the climatological zones located within the state, thus producing only four IDF curves.</td></tr>
<tr><td colspan="2">17. Key Words
Rainfall-Intensity-Duration-Frequency (IDF) Curves, Climatological Areas, Bulletin 71, Theissan Polygons</td><td colspan="2">18. Distribution Statement
Unlimited with the approval of the Kentucky Transportation Cabinet</td></tr>
<tr><td>19. Security Classif. (of this report)</td><td>20. Security Classif. (of this page)</td><td>21. No. of Pages</td><td>22. Price</td></tr>
</table>

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The purpose of this study was to revise and update the already existing Rainfall Intensity-Duration-Frequency Curves for the Commonwealth of Kentucky. There were basically four steps in the process: determine the Areas of Influence; gather data from those areas; analyze the data; and produce the curves.

During the course of this project, it was determined that two major revisions in the procedures were necessary. The first revision was to change the way the Areas of Influence were determined; and the second revision was to utilize some data that was generated mathematically. As a result, there are now only four curves that represent the state instead of nine.

The first procedural change was in the way Areas of Influence were determined. Historically the Areas of Influence were determined using Thiessen polygons. The focal points for these polygons were First Order Weather Stations. However, only three out of the nine First Order Stations used to generate the curves were located within Kentucky. Changing the way the Areas of Influence were determined improved the accuracy of the curves. In accordance with Bulletin 71, r Areas of Influence were established based on the four climatological zones within Kentucky. This new procedure made use of data taken from Cooperative Weather Stations as well as First Order Stations. Thus, only data within the Commonwealth of Kentucky was used to establish the curves.

The second procedural change was in the amount of data, and the way the data was collected. Previously, data was solicited from the State Climatologist, Glen Conner. He supplied data for 5-, 10-, 15-, 20-, 30-, 45-, 60-, 80-, 100-, and 120-minute time intervals. However, First Order Stations no longer collect data for all those time periods, now they only collect hourly data. Some Cooperative Climate Stations do collect data for multiple time intervals, but they are few and far between. As a result, some of the data for short rainfall durations had to be generated mathematically using linear regression.

Three sets of curves were developed and included in this report: the nine traditional curves based on First Order Weather Station locations, the four curves based on climatological areas, and the four curves after linear regression was applied. Th two sets of curves were compared and the Study Advisory Committee recommended that the curves based on Climatological Areas be used. It is further recommended that Climatological Areas be used in the future when developing Rainfall Intensity-Duration Frequency Curves.

Funding for this project came from the Kentucky Transportation Cabinet under Research Study KYSPR 98-178, entitled "Revision of Rainfall Intensity-Duration Curves for Kentucky".

1. INTRODUCTION

Rainfall Intensity-Duration Frequency Curves (IDF Curves) are graphical representations of the amount of water that falls within a given period of time. These curves are used to help predict when an area will be flooded, or to pinpoint when a certain rainfall rate or a specific volume of flow will recur in the future.

In Kentucky, rainfall IDF curves are used in conjunction with the Rational Method[1] to calculate runoff from a particular watershed. The information from the curves is then used in hydraulic design to size culverts and pipes. Figure 1 below, shows an example of a Rainfall Intensity-Duration Curve.

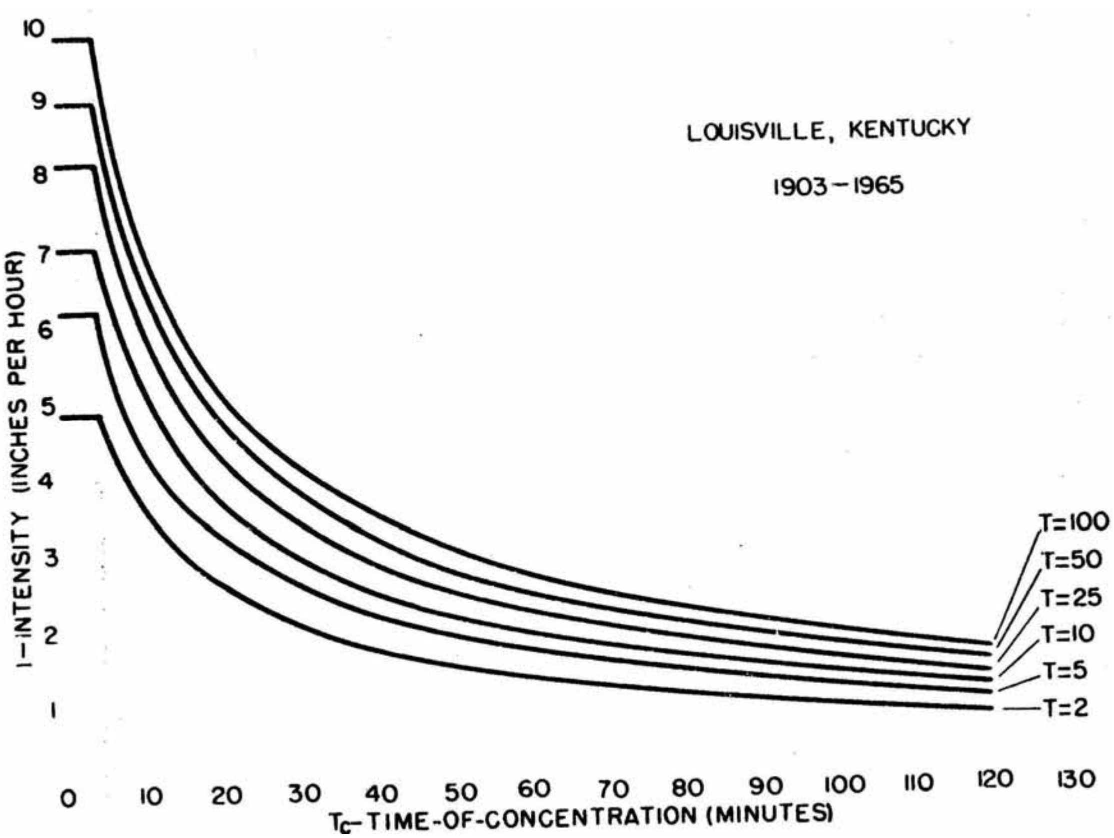


Figure 1. 1968 Rainfall Intensity-Duration-Frequency Curve for Louisville, Kentucky.

[1]The Rational Method determines design flow and is used when high accuracy of runoff rate is not required and the drainage area is less than 300 acres.

1.1 BACKGROUND

Engineers must often consider storm run-off when building a new structure. Rainfall Intensity-Duration-Frequency Curves are used to aid the engineer when creating the design. Engineers have been using IDF curves in the United States since 1935.

David Yarnell developed the first “intensity-frequency maps” for the United States in 1935. Yarnell studied 30 years of rainfall intensity-frequency (18). In 1955, the U.S. Weather Bureau (USWB) and the Soil Conservation Service (SCS) defined the depth-area-duration-frequency regime in the United States.

“In 1961 the U.S. Weather Bureau published the Rainfall Frequency Atlas of the United States, commonly known as Hershfield’s Technical Paper No. 40 (TP-40). This document contains rainfall depth maps of the United States for the 1-, 2-, 5-, 10-, 25-, and 100-year recurrence interval storms for durations of 1-,2-,3-,6-,12-, and 24-hours for areas east of the 105° meridian. For storm durations of less than 1 hour the TP-40 information was superseded by NOAA’s technical Memorandum “NEW HYDRO –35.” The IDF curves currently in use in Kentucky are governed by Technical Paper 40 (TP-40).

However, TP-40 wasn’t always accurate. “One of the problems with TP-40 is that its 100-year, 24-hour values were exceeded too frequently in certain regions of the Midwest (13, p. 1). To combat this problem, the National Oceanic and Atmosphere Administration’s Midwestern Climate Center has produced a new study that applies to nine states across the Midwest (Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Missouri, Ohio, and Wisconsin) and it is referred to as Bulletin 71. Bulletin 71 has a much larger, longer sample of precipitation data that was available for previous U.S. studies (13, p. 1). It is a “combination of appropriate statistical techniques, guided by available meteorological and climatological knowledge of atmospheric processes (13, p.2)”

E.M. West and W. H. Sammons generated the first curves for the Commonwealth of Kentucky in 1955 (Kentucky Department of Highways, Division of Research, Report No. 108, “A Study of Runoff from Small Drainage Areas and the Opening in Attendant Drainage Structures”). They were updated in 1968 by K.D. Clark (Kentucky Department of Highways, Division of Research, Report No. 250, “Application of Standford Watershed Model Concepts to Predict Flood Peaks for Small Drainage Areas”) and again in 1985 by Jessie Mays. The curves have not been updated since that time.

As a result, the Kentucky Transportation Cabinet (KyTC) approved Research Study KYSPR 98-178, entitled "Revision of Rainfall Intensity-Duration Curves for Kentucky" in 1998. The objective of this research study was to revise and update the rainfall-intensity-duration-frequency curves for Kentucky to include weather data from 1984 through the present.

To update the curves, four basic steps must be followed: determine the Areas of Influence; gather data from those areas; analyze the data; and produce the curves.

2. DETERMINE AREAS OF INFLUENCE

An "Area of Influence" must be determined before a rainfall intensity-duration curve can be developed. Rainfall data is gathered from many different stations throughout the Commonwealth. "Kentucky has an area of 40,395 square miles" (8), therefore a great number of weather stations are required to produce an accurate picture. The rainfall data that is gathered from those stations must be sorted into specific groups to be of use. Establishment of these areas or the "Areas of Influence", allows the researcher to group the data together for analysis. Curves are then developed to provide a graphical representation of the amount of water that falls within a given period of time on that particular area.

Traditionally an Area of Influence is determined by using Thiessen Polygons. However, Bulletin 71 introduced a new method to create the Area of Influence, use of similar Climatological Zones. Those methods are described in the following paragraphs.

2.1 THIESSEN POLYGONS

In the past, two things defined Areas of Influence for IDF curves: the location of the First Order Weather Station and the Thiessen Polygon that is drawn around the First Order Weather Station. First Order Weather Stations provide hourly and daily rainfall data. These stations are certified by the National Weather Service (NWS) and by the Federal Aviation Association's (FAA) Weather Office.

Glen Conner, State Climatologist for the Commonwealth of Kentucky, explained how the sites for First Order Weather Stations were chosen. "Selection of sites was based on need. Aircraft have the greatest need for weather information. First Order Weather Stations were selected dependent upon whether or not a city had a large airport." Kentucky has only three cities with First Order Weather Stations: Hebron (Greater Cincinnati Airport), Lexington (Bluegrass Airport) and Louisville (Stanford Field).

However, these three did not geographically represent the entire state. Therefore, six other stations were selected. All six were close to the State lines, but were, nonetheless, outside Kentucky. There are four in Tennessee, one in West Virginia, and one in either Illinois or Missouri depending on the time period. Table 1 lists the locations of the First Order Stations used to develop the curves in 1968, 1985, and 1997.

Table 1. Locations of First Order Weather Stations.

Location	1968	1985	1997
Cairo, Il	X	X	X
Hebron, KY	X (referred to as: Cincinnati, OH)	X (referred to as: Covington, KY)	X (referred to as: Hebron, KY)
Evansville, IN	X	X	X
Knoxville, TN	X	X	X
Lexington, KY	X	X	X
Louisville, KY	X	X	X
Nashville, TN	X	X	X
Parkersburg, WV	X	X	X (changed to: Huntington, WV)
Wytheville, VA	X	X (changed to: Bristol, TN)	X (changed to: Bristol, TN)

Once the First Order Stations were established the next step towards creating the Areas of Influence was to set up Thiessen Polygons. This method was developed by A. H. Thiessen in 1911 and is still a popular method for determining an Area of Influence. Thiessen Polygons are established by drawing a series of lines around each First Order Station. The steps are as follows:

1. Draw a straight line from the center of one station to the centers of the surrounding stations.
2. Then draw perpendicular lines through the midpoints of the lines connecting the stations. These bisecting lines are the lines that create the polygon.
3. When two lines intersect, both lines stop, establishing the ending point for one side of the polygon.

The Thiessen Polygons were named according to the First Order Station that was used to create them. Table 2 lists the counties that fall into each Thiessen Polygon. Some counties are divided into two different polygons. The same data was used in both polygons to determine peak flow for that Area of Influence.

Table 2. Counties within Thiessen Polygons.

BRISTOL REGION

Floyd	Knott	Letcher	Pike
Harlan	Leslie	Perry	

CAIRO REGION

Ballard	Crittenden	Hickman	Marshall
Calloway	Fulton	Livingston	McCracken
Carlisle	Graves	Lyon	Trigg

CINCINNATI REGION

Boone	Carroll	Kenton	Owen
Bracken	Gallatin	Lewis	Pendleton
Campbell	Grant	Mason	Robertson

EVANSVILLE REGION

Breckinridge	Daviess	Hopkins	Trigg
Butler	Edmonson	McLean	Union
Caldwell	Grayson	Muhlenberg	Warren
Christian	Hancock	Ohio	Webster
Crittendon	Henderson	Todd	

HUNTINGTON REGION

Boyd	Floyd	Lewis	Perry
Breathitt	Greenup	Magoffin	Pike
Carter	Johnson	Martin	Rowen
Elliott	Knott	Menifee	Wolfe
Fleming	Lawrence	Morgan	

KNOXVILLE REGION

Bell	Harlan	McCreary	Wayne
Clay	Knox	Monroe	Whitley
Clinton	Laurel	Pulaski	
Cumberland	Leslie	Russell	

LEXINGTON REGION

Adair	Fleming	Lincoln	Pulaski
Anderson	Franklin	Madison	Robertson
Bath	Garrard	Marion	Rockcastle
Bourbon	Grant	Mason	Rowan
Boyle	Green	Menifee	Russell
Bracken	Harrison	Mercer	Scott
Breathitt	Henry	Metcalfe	Shelby
Casey	Jackson	Nelson	Spencer
Clark	Jessamine	Nicholas	Taylor
Clay	Laurel	Owen	Washington
Cumberland	Lee	Owsley	Wolfe
Fayette	Leslie	Perry	Woodford

LOUISVILLE REGION

Adair	Grayson	Larue	Shelby
Barren	Green	Marion	Spencer
Breckinridge	Hardin	Meade	Taylor
Bullitt	Hart	Metcalfe	Trimble
Carroll	Henry	Nelson	Washington
Edmonson	Jefferson	Oldham	

NASHVILLE REGION

Allen	Edmonson	Todd
Barren	Logan	Trigg
Butler	Metcalfe	Warren
Christian	Monroe	
Cumberland	Simpson	

Figure 2 shows the original Areas of Influence established in 1968. Figure 3 shows the changes in the Thiessen Polygons that resulted when the Wytheville, VA First Order Weather Station was replaced by Bristol, TN station in 1985. Figure 4 shows the changes made in the Thiessen Polygons in 1998. Those changes resulted when two outlying First Order Stations were replaced. The Cairo, IL station was replaced by the Cape Girardeau, MO station, and the Parkersburg, WV station was replaced with the Huntington, WV station. Data is still available for Parkersville (1981-96), however, Huntington was used to update the curves as it was in closer proximity to Kentucky and had more available data (1961-96).

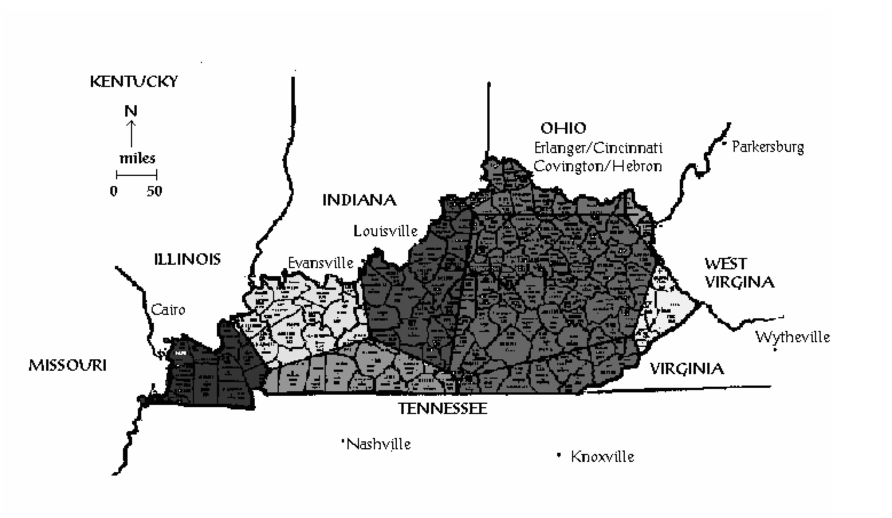


Figure 2. Thiessen Polygons Used to Determine Areas of Influence in 1968.

Changes in First Order stations were necessitated because data was no longer available at those stations or because closer First Order Stations would provide data that more closely resembled Kentucky conditions.

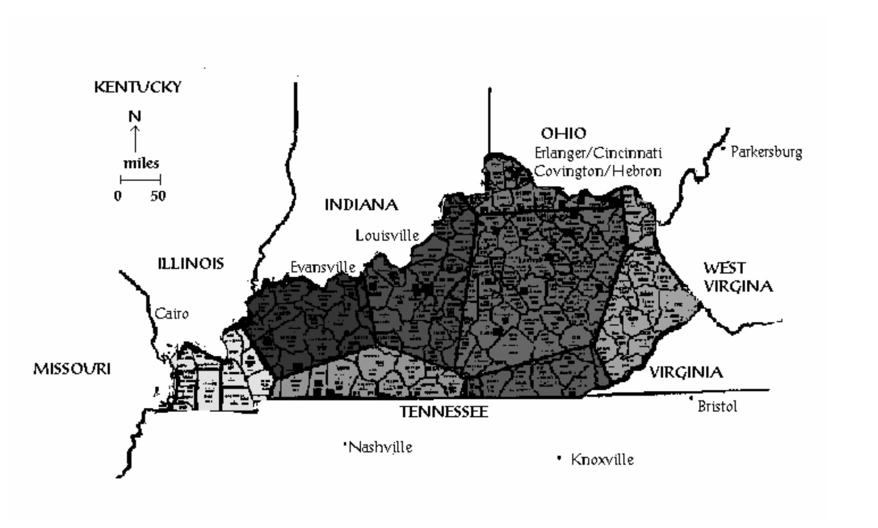


Figure 3. Thiessen Polygons Used To Determine Areas of Influence in 1985.

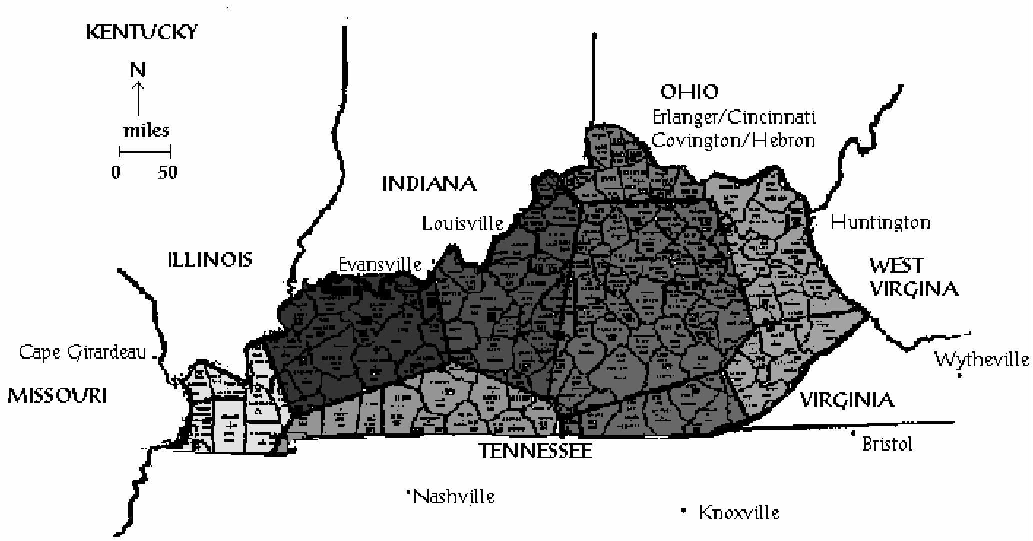


Figure 4. Thiessen Polygons Used to Determine Areas of Influence in 1998.

2.2 CLIMATOLOGICAL AREAS

Bulletin 71, the latest publication from the Midwestern Climate Center, suggests the use of Climatological Zones to determine the Areas of Influence. Climatological Zones are based on national climates and use of Climatological Areas instead of the traditional Thiessen Polygons produces curves that are more representative of a particular area.

Kentucky has four very distinct climate patterns. James Angel of the Midwestern Climate Center and author of the "Rainfall Frequency Atlas of the Midwest" conducted extensive research, gathered data from each state, and produced rainfall distribution maps. From this data, it became apparent that Kentucky was divided into four distinct divisions: Western, Central, Blue Grass and Eastern. Figure 5, outlines the four Climatological Areas of Influence in Kentucky.

The Western Division contains 26 counties, the Central Division has 24 counties, the Blue Grass Division has 35 counties, and the Eastern Division has 35 counties. The counties are listed in Table 3.

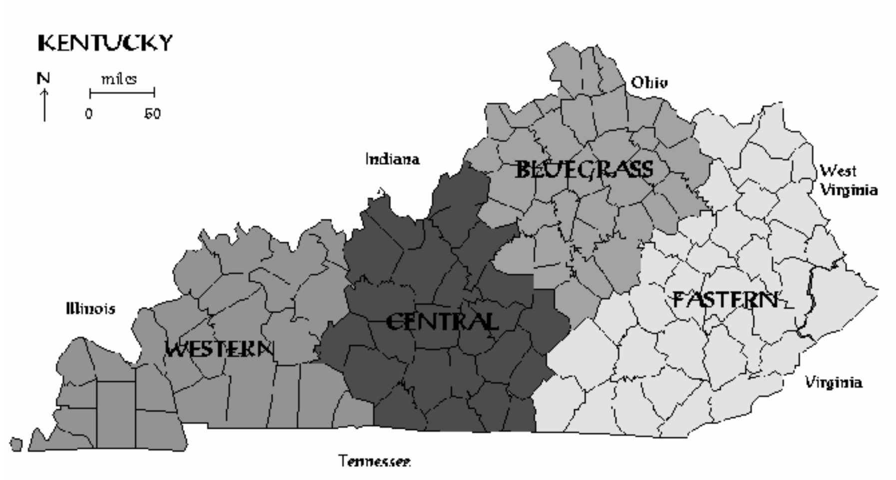


Figure 5. Climatological areas within Kentucky.

Table 3. Counties within Climatological Areas of Influence.

WESTERN	CENTRAL	BLUEGRASS	EASTERN
			Bell
Ballard	Adair	Anderson	Boyd
Caldwell	Allen	Bath	Breathitt
Calloway	Barren	Boone	Carter
Carlisle	Breckinridge	Bourbon	Clay
Christian	Bullitt	Boyle	Elliott
Crittenden	Butler	Bracken	Estill
Daviess	Casey	Campbell	Floyd
Fulton	Clinton	Carroll	Greenup
Graves	Cumberland	Clark	Harlan
Hancock	Edmonson	Fayette	Jackson
Henderson	Grayson	Fleming	Johnson
Hickman	Green	Franklin	Knott
Hopkins	Hardin	Gallatin	Knox
Livingston	Hart	Garrard	Laurel
Logan	Jefferson	Grant	Lawrence
Lyon	Larue	Harrison	Lee
Marshall	Marion	Henry	Leslie
McCracken	Meade	Jessamine	Letcher
McLean	Metcalfe	Kenton	Lewis
Muhlenberg	Monroe	Lincoln	Magoffin
Ohio	Nelson	Madison	Martin
Simpson	Russell	Mason	McCreary
Todd	Taylor	Mercer	Menifee
Trigg	Warren	Montgomery	Morgan
Union		Nicholas	Owsley
Webster		Oldham	Perry
		Owen	Pike
		Pendleton	Powell
		Robertson	Pulaski
		Scott	Rockcastle
		Shelby	Rowan
		Spencer	Wayne
		Trimble	Whitley
		Washington	Wolfe
		Woodford	

Figure 6 is an excerpt from Bulletin 71 (13, p.56). This rainfall distribution map was used to illustrate the divisions that climate imposes on Kentucky.

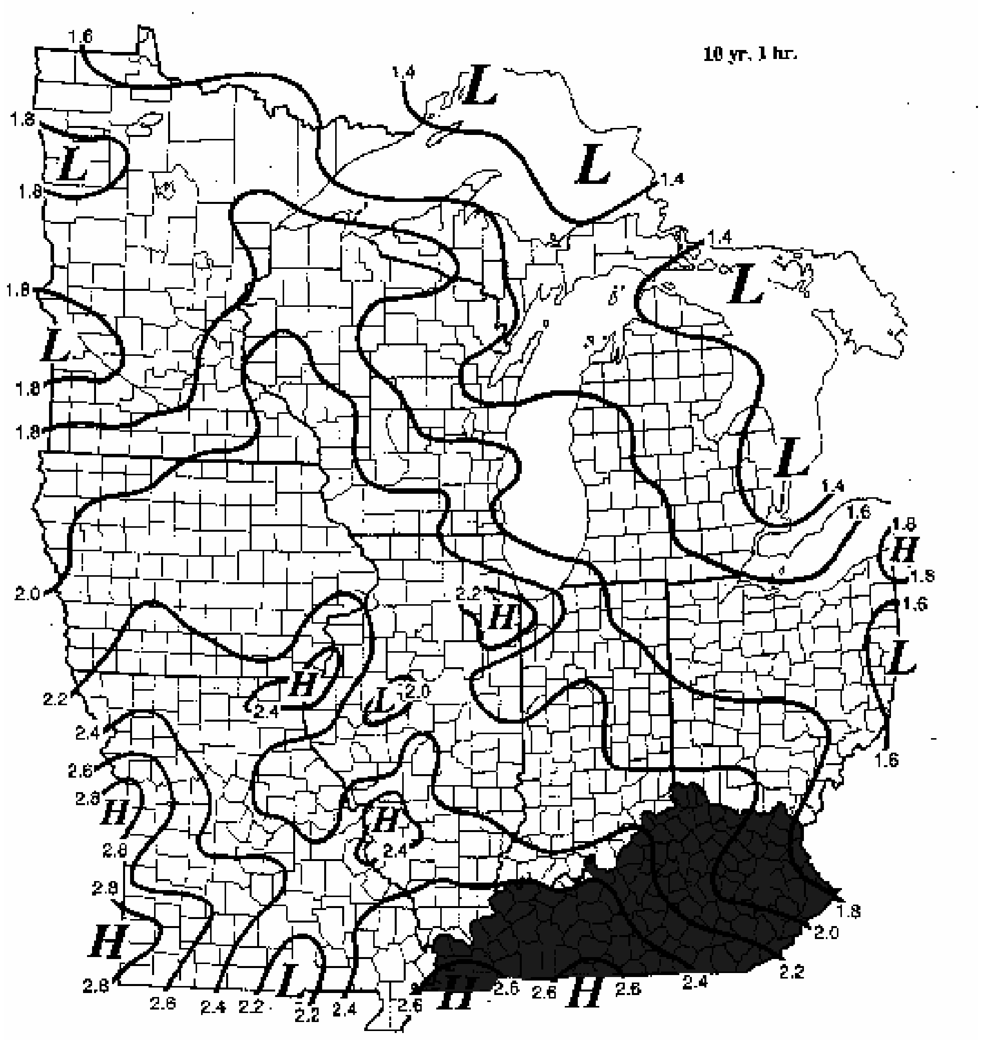


Figure 6. Rainfall distribution map shows the Midwest Climatological Areas. Drawing provided by Dr. Jim Angel, Midwest Climate Center.

“Kentucky is divided into five major physiographic regions: the Mississippi Embayment or Jackson Purchase in the west, the Mississippian Plateaus or Pennyrile, the Western Coal Field, the Bluegrass, and the Eastern Coal Field.” (8). The differences in geography and topography reflect the differences in climate and the amount of rainfall that each area receives. Figure 7 shows a physiographic map of Kentucky produced by the Kentucky Geological Survey.

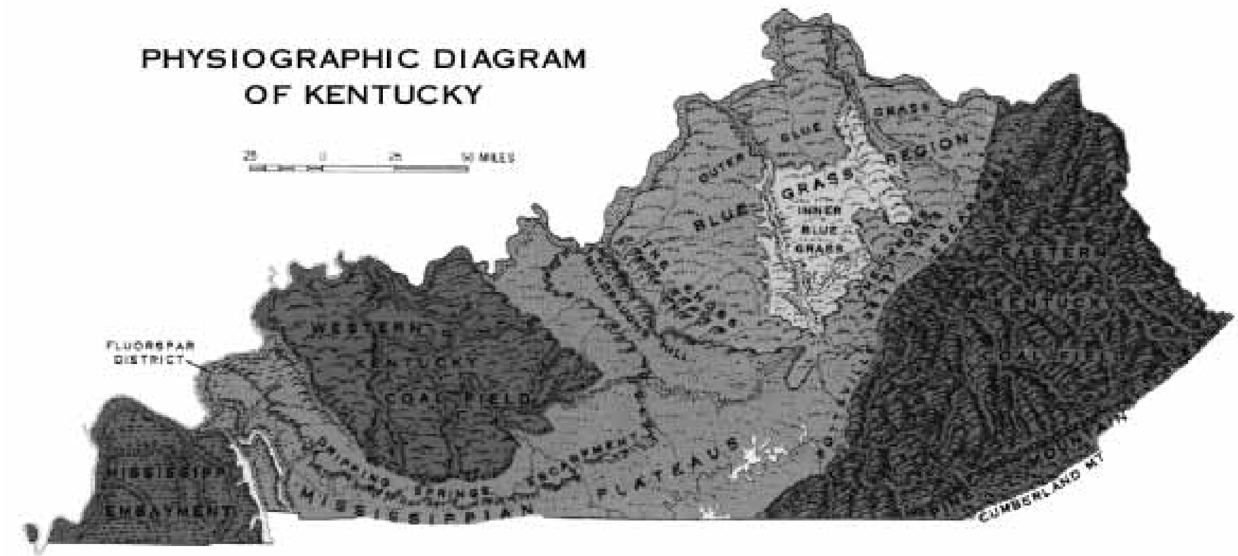


Figure 7. Physiographic Map of Kentucky. Produced by Kentucky Geological Survey (undated).

When the Climatological Areas of Influence are superimposed on the Physiographic Diagram of Kentucky as in Figure 8, it is obvious that the two maps coincide exactly in the Bluegrass and Eastern areas. However, the Western and Central areas differ somewhat from the climatological areas.

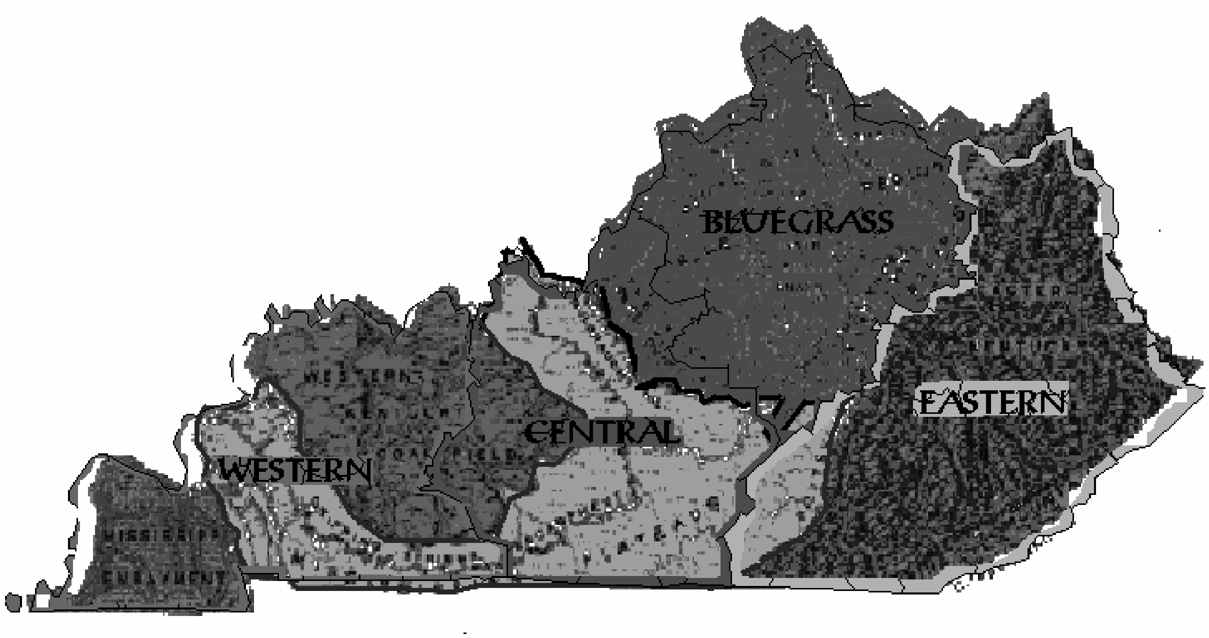


Figure 8. Climatological Areas of Influence superimposed on Physiographic Map of Kentucky.

The *Western Area of Influence* has three separate physiographic areas within it. They include parts of the Western Kentucky Coal Field, the Pennyrile Region and the Jackson Purchase. The Western Kentucky Coal Field is south of the Ohio River and just above the Pennyrile region. The Pennyrile region "stretches from the Land Between the Lakes, in the west, across the state to the Pottsville Escarpment in the east. It is a Mississippian plateau with a large karst region that includes Mammoth Cave." (11) The Jackson Purchase is located in the extreme western part of the state. "It is bounded by three rivers, the Mississippi, the Ohio and the Tennessee (now called Kentucky Lake). This area includes the lowest elevations in the state. It is located in the Gulf Coastal Plain of the central United States and consists of alluvial deposits and loess. (12) However, this area produced little data and was therefore included in the Western Area of Influence.

The *Central Area of Influence* is made up of the Louisville portion of the Bluegrass geographical region, the Western Kentucky Coal Field area and the central part of the Pennyrile region. Jefferson County has several rainfall data sites and provides adequate data for a curve to be developed for that area alone. The Jefferson County area hosts a population of two million and has a central location.

The *Bluegrass Area of Influence* is governed by the Bluegrass region of Kentucky. It too has geographic barriers that influence the type of weather that it receives. "The Bluegrass area is bordered by the Ohio River on the west and north sides and by the Knobs, a ring of hills to the east, south, and west. This area is mostly pastureland. The underlying limestone is often visible at the surface, in road cuts, and where eroded by streams - most dramatically in the Kentucky River palisades. The Bluegrass Area includes one of Kentucky's largest cities, Lexington, and the urban area of Northern Kentucky." (9)

The *Eastern Area of Influence* is located in the geographic region referred to as the "Eastern Kentucky Coal Field". "This area is east of the Appalachian Mountains and covers the area across the Cumberland Plateau to the Pottsville Escarpment." (10)

The link between climate and physical geography is very strong. Therefore, establishing Areas of Influence based on Climatological Areas follows this logical process. Once the Areas of Influence have been established, the next step is to collect data from within those Areas of Influence.

3.0 DATA COLLECTION

Data gathering was perhaps, the most difficult part of the project. The data used to develop the 1968 and 1985 IDF curves consisted of recorded maximum annual rainfall values for short durations of 5-, 10-, 15-, 30-, 60- and 120-minutes for the nine First Order Stations. That data was supplied by Glen Conner, State Climatalogist for Kentucky. However, according to Conner, data is no longer collected for such short durations.

Since 1985, data has only been collected for 15-minute, 60-minute, and 24-hour intervals. Values for shorter durations are statistically calculated from the 24-hour data. The State Climatologist, the National Weather Service, and the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC) all concur that this method of data collection is more beneficial, less time consuming, and more economical. Using available data and then generating the short duration data reduces the margin of error introduced by various factors. Some of these factors include: problems with instrumentation, individual observational techniques, as well as rain gage location, exposure, and land-use changes.

In the past, only data from First Order Weather Stations was used to develop IDF Curves. However, improvements in instrumentation used for gathering rainfall data has resulted in greater accuracy at the Co-Operative (Co-Op) Weather Stations. "Cooperative Climate Stations, meet specifications of the World Meteorological Organization (WMO). Co-Op stations send in a monthly report, which includes daily temperatures, rainfall and snowfall. (5, p. 3)"

As a result, it is not necessary to go outside the state to obtain rainfall data. Combining First Order and Co-op Weather station data allows the researcher to use only data from within the state, making the resulting IDF curves more accurate and specific to the region. The rainfall data for this study was obtained from EarthInfo CD-ROM's. The data for the CD was supplied by the National Climatic Data Center and it reflects the many changes and corrections that NCDC has made to their databases over the past few years.

The 15-minute data was obtained from EarthInfo's NCDC Fifteen-minute Precipitation CD. "The data is from the NCDC TD-3260 file. Fewer stations supply fifteen-minute data and the periods of record are shorter than the hourly data. The CD has measurements dating from 1971." (4, p.1).

The 30-minute data was obtained from EarthInfo's NCDC Hourly Precipitation CD. This CD contains precipitation data from the NCDC TD-3240 file. "Generally, periods of record begin in 1948, but some date to the beginning of the century." (4, p. 1)

The daily rainfall data was obtained from EarthInfo's NCDC Summary of the Day CD. The data was supplied from the National Climatic Data Center's TD-3200 file, as corrected by NCDC's Validated Historical Daily Data project (4, p. 1).

4. DATA ANALYSIS

Once the data was collected, it was exported and analyzed by use of a computer program. Three programs were written for each type of data. The computer programs were written in Practical Extraction and Report Language (Perl). "Perl is a language for easily manipulating text, files, processes. Perl provides a more concise and readable way to do many jobs that were formerly accomplished by programming in the C language or one of the shells. Perl also shares features with many of the UNIX utilities that a shell would invoke" (18, p. xi). The differences in the amount and the type of data required that two separate computer programs be written.

Evaluation of the data required four steps:

Step 1: The data was analyzed by computer to determine maximum or peak Rainfall for each year of data for a specific station.

Step 2: That data was then imported into an Excel spreadsheet and sorted according to county. If a county had more than one set of data, as many of them did, then the maximum value per year was selected as the representative value for the county.

Step 3: The counties were then divided into Areas of Influence. Three different Areas of Influence were used:

a) nine First Order stations using data from First Order stations ONLY (using original nine Theissan Polygons),
b) nine First Order stations using only First Order and Co-Op data from within the state (using the original nine Theissan Polygons),
c) four climatological areas using only First order and Co-op data from within the state (new Climatological Zone method).

Step 4: All counties falling into a particular Area of Influence were evaluated and the maximum value for each year was extracted as the representative value for the Area.

5. DEVELOPMENT OF RAINFALL INTENSITY DURATION FREQUENCY CURVES.

Once the data has been sorted into the various Areas of Influence, curve development begins. IDF curves are used when storm information is needed to design a structure. In Kentucky, rainfall intensity-duration-frequency curves are used in conjunction with the Rational Method[1] to calculate peak runoff from a particular watershed.

Most areas have several rain gages and many years of data. Graphical representations are developed to present the rainfall data in a usable format. Each graph has six curves on it, each one representing a different storm frequency. They usually represent the 2-, 5-, 10-, 25-, 50-, and 100-year storms. Rainfall intensity is on the y-axis and is measured in inches per hour or in mm/h. Storm duration is on the x-axis and is measured in minutes. The amount of rain that is produced by a particular storm is site specific.

When a particular rainfall is referred to as a 2-hr, 100-yr storm, that means that the rain will last for two hours (duration) and will only be equaled or exceeded once every one hundred years (frequency) in that particular area. Understanding the significance of each curve, it is then a simple matter to determine the amount of rainfall (intensity) for that particular area during that time period. For example:

1. Select the 100-year IDF curve,
2. find the 2-hr mark on the x-axis (120 minute),
3. determine where the curve and the graph line intersect, then follow it straight across to the y-axis to determine the amount of rain.

Although using the curves is quite simple, the development of the curves is much more involved.

5.1 GUMBEL THEORY OF DISTRIBUTION

There are several methods that can be used to generate Rainfall-Intensity Duration Frequency Curves (IDF Curves). Of primary concern to the Kentucky Transportation Cabinet is maximum flood peaks, so the Gumbel Type I distribution methodology was selected to perform the flood-probability analysis. The Gumbel theory of distribution is relatively simple and uses only extreme events (maximum values or peak rainfalls). It is the "first asymptotic distribution of extreme values (16, p. 361)." "Using only peak rainfall data to represent each year, reduces the probability of error to less than 0.5 percent. (16, p. 248)". The Gumbel Method calculates the 2-, 5-, 10-, 25-, 50-, and 100-year return intervals for each duration period and requires several calculations (16, p. 251-252).

Step 1: Define the frequency factor, or K value, that correlates with the number of years of available data. The K values are calculated values and are derived from the following equation.

$$\mathbf{p = 1 - e^{-e^{-y}}} \qquad \textbf{(1)}$$

p = probability of a given flow being equaled or exceeded
e = base of napierian logarithms
y = reduced variate

The reduced variate, y, is a function of probability and should be used with a particular time period. The calculated y-values are found in Table 4.

$$\mathbf{y = a\,(X - X_f)} \qquad \textbf{(2)}$$

y = reduced variate
a = dispersion parameter
X = extreme data values
X_f = mode of the distribution

Values for the parameters **a** and $\mathbf{X_f}$ are based on the least-squares analysis**.** "Gumbel's solution minimizes the squares of the deviations measured perpendicular to the derived line of expected extremes (16, p. 251)."

$$\mathbf{a = \sigma_n/\sigma_x} \qquad \textbf{(3)}$$

$$\mathbf{X_f = \mathit{X} - \sigma_x(y_n/\sigma_n)} \qquad \textbf{(4)}$$

a = dispersion parameter
σ_n = reduced standard deviation
σ_x = standard deviation
X **=** arithmetic mean
y_n **=** reduced variate

Table 4. Values for reduced variate, y, and the corresponding return periods. (16)

Return Period (years)	Reduced Variate (y)	Return Period (years)	Reduced Variate (y)	Return Period (years)	Reduced Variate (y)	Return Period (years)	Reduced Variate (y)
1.5	-0.09405	56	4.01636	55	5.04015	1000	6.90725
2	0.36651	57	4.03421	60	5.10288	50	6.95606
3	0.90272	58	4.05176	65	5.11785	1100	7.00261
4	1.27189	59	4.06900	70	5.13281	50	7.04704
5	1.49994	60	4.08594	175	5.16188	1200	7.08972
6	1.70199	61	4.10261	80	5.19014	50	7.13050
7	1.86983	62	4.11901	85	5.21762	1300	7.16979
8	2.01342	63	4.13514	90	5.24434	50	7.20755
9	2.13890	64	4.15101	95	5.27037	1400	7.24387
10	2.25037	65	4.16664	200	5.29581	50	7.27891
11	2.35062	66	4.18202	10	5.34473	1500	7.31286
12	2.44171	67	4.19717	20	5.39134	50	7.34565
13	2.52520	68	4.21210	30	5.43591	1600	7.37748
14	2.60223	69	4.22680	40	5.47855	50	7.40820
15	2.67375	70	4.24130	250	5.51946	1700	7.43817
16	2.74049	71	4.25559	60	5.55874	50	7.46715
17	2.80305	72	4.26967	70	5.59657	1800	7.49522
18	2.86193	73	4.28356	80	5.63301	50	7.52275
19	2.91752	74	4.29726	90	5.66814	1900	7.54942
20	2.97020	75	4.31078	300	5.70213	50	7.57541
21	3.02022	76	4.32411	10	5.73496	2000	7.60065
22	3.06787	77	4.33727	20	5.76676	2100	7.64948
23	3.11335	78	4.35026	30	5.79757	2200	7.69615
24	3.15685	79	4.36308	40	5.82746	2300	7.74047
25	3.19853	80	4.37574	350	5.85652	2400	7.78300
26	3.23855	81	4.38823	60	5.88470	2500	7.82385
27	3.27702	82	4.40059	70	5.91215	2600	7.86320
28	3.31407	83	4.41278	80	5.93884	2700	7.90075
29	3.34980	84	4.42483	90	5.96487	2800	7.93740
30	3.38429	85	4.43673	400	5.99021	2900	7.97248
31	3.41763	86	4.44849	20	6.03904	3000	8.00640
32	3.44989	87	4.46012	40	6.08565	3200	8.07084
33	3.48115	88	4.47161	60	6.13015	3400	8.13159
34	3.51146	89	4.48297	80	6.17277	3600	8.18858
35	3.54089	90	4.49421	500	6.21361	3800	8.24262
36	3.56946	91	4.50532	20	6.25286	4000	8.29393
37	3.59725	92	4.51633	40	6.29062	4200	8.34284
38	3.62427	93	4.52719	60	6.32705	4400	8.38932
39	3.65051	94	4.53794	80	6.36219	4600	8.43387
40	3.67625	95	4.54859	600	6.39608	4800	8.47659
41	3.70126	96	4.55911	25	6.43695	5000	8.51709
42	3.72564	97	4.56954	50	6.47618	5500	8.61273
43	3.74945	98	4.57983	75	6.51396	6000	8.69964
44	3.77272	99	4.59004	700	6.55035	6500	8.78027
45	3.79544	100	4.60012	25	6.58549	7000	8.85379
46	3.81767	5	4.64916	50	6.61944	7500	8.92345
47	3.83941	10	4.69589	75	6.65224	8000	8.99274
48	3.86068	15	4.74056	800	6.68399	8500	9.04884
49	3.88152	20	4.78330	25	6.71480	9000	9.10540
50	3.90193	125	4.82431	50	6.74463	9500	9.15977
51	3.92193	30	4.86369	75	6.77363	10,000	9.21029
52	3.94154	35	4.90153	900	6.80185	15,000	9.61785
53	3.96078	40	4.93805	25	6.82924	20,000	9.90346
54	3.97964	45	4.97325	50	6.85598	25,000	10.12661
55	3.99817	150	5.00726	75	6.88197	50,000	10.81977

The calculated frequency factors, or K values, have been condensed and can be obtained from Table 5. In this study interpolation was used to calculate between values to arrive at a specific value for a particular number of years.

Table 5. Values of K for the Extreme-Value Distribution. (16, p. 346)

Return Period (years)	Prob-ability y	Reduced variate y	Record Length 20 yr.	Record Length 30 yr.	Record Length 40 yr.	Record Length 50 yr.	Record Length 100 yr.	Record Length 200 yr.	Record Length Infinity
2	0.50	0.367	-0.147	-0.152	-0.155	-0.156	-0.160	-0.162	-0.164
5	0.20	1.500	0.919	0.866	0.838	0.820	0.779	0.755	0.719
10	0.10	2.250	1.62	1.54	1.50	1.47	1.40	1.36	1.30
25	0.04	3.200	2.45	2.33	2.265	2.22	2.13	2.07	1.99
50	0.02	3.902	3.18	3.03	2.94	2.89	2.77	2.70	2.59
100	0.01	4.600	3.84	3.65	3.55	3.49	3.35	3.27	3.14

Step 2: Use the available data to calculate the mean and the standard deviation. The following statistical formulas produce those values.

$$\text{Mean: } \boldsymbol{X} = \Sigma X/n \tag{1}$$

$$\text{Standard Deviation: } \sigma_n = \frac{\sqrt{\Sigma X^2 - \boldsymbol{X} * \Sigma X}}{n - 1} \tag{2}$$

NOTE: Microsoft Excel's Add-In, Data Analysis, provides these Descriptive Statistics.

Step 3: The calculated values for the mean and the standard deviation, as well as the K value are then used in the following equation to produce the magnitude of a particular flood.

$$X = \boldsymbol{X} + \sigma_x/\sigma_n\,(y - y_n) \tag{4}$$

This formula simplifies to the more generalized form:

$$X = \boldsymbol{X} + K\sigma_x \tag{5}$$

$$\therefore\ K = (y - y_n)/\ \sigma_n \tag{6}$$

Where:

X = Flood of specific probability y_n = expected mean of reduced extremes
y = reduced variate σ_x = standard deviation of the series
$\boldsymbol{X}$ = mean of the flood series σ_n= reduced standard deviation
K = frequency factor defined by a specific distribution, a function of the probability level of X

The theoretical values for the expected means standard deviations are based on sample size and can be found in Table 6.
NOTE: All answers should be rounded to three significant digits.

Table 6. Values for reduced mean, y_n, reduced standard deviation, σ_n, corresponding to various return periods. (1, p. 152.)

N	Reduced Mean y_n									
(yr.)	0	1	2	3	4	5	6	7	8	9
10	0.4952	0.4996	0.5035	0.5070	0.5100	0.5128	0.5157	0.5181	0.5202	0.5220
20	0.5236	0.5252	0.5268	0.5283	0.5296	0.5309	0.5320	0.5332	0.5343	0.5353
30	0.5362	0.5371	0.5380	0.5388	0.5396	0.5402	0.5410	0.5418	0.5424	0.5430
40	0.5436	0.5442	0.5448	0.5453	0.5458	0.5463	0.5468	0.5473	0.5477	0.5481
50	0.5485	0.5489	0.5493	0.5497	0.5501	0.5504	0.5508	0.5511	0.5515	0.5518
60	0.5521	0.5524	0.5527	0.5530	0.5533	0.5535	0.5538	0.5540	0.5543	0.5545
70	0.5548	0.5550	0.5552	0.5555	0.5557	0.5559	0.5561	0.5563	0.5565	0.5567
80	0.5569	0.5570	0.5572	0.5574	0.5576	0.5578	0.5580	0.5581	0.5583	0.5585
90	0.5586	0.5587	0.5589	0.5591	0.5592	0.5593	0.5595	0.5596	0.5598	0.5599
100	0.5600									
N	Reduced Standard Deviation σ_n									
(yr.)	0	1	2	3	4	5	6	7	8	9
10	0.9496	0.9676	0.9833	0.9971	1.0095	1.0206	1.0316	1.0411	1.0493	1.0565
20	1.0628	1.0696	1.0754	1.0811	1.0864	1.0915	1.0961	1.1004	1.1047	1.1086
30	1.1124	1.1159	1.1193	1.1226	1.1255	1.1285	1.1313	1.1339	1.1363	1.1388
40	1.1413	1.1436	1.1458	1.1480	1.1499	1.1519	1.1538	1.1557	1.1574	1.1590
50	1.1607	1.1623	1.1638	1.1658	1.1667	1.1681	1.1696	1.1708	1.1751	1.1734
60	1.1747	1.1759	1.1770	1.1782	1.1793	1.1803	1.1814	1.1824	1.1834	1.1844
70	1.1854	1.1863	1.1873	1.1881	1.1890	1.8980	1.1906	1.1915	1.1923	1.1930
80	1.1938	1.1945	1.1953	1.1959	1.1967	1.1973	1.1980	1.1987	1.1994	1.2001
90	1.2007	1.2013	1.2020	1.2026	1.2032	1.2038	1.2044	1.2049	1.2055	1.2060
100	1.2065									

Step 4: Double-Mass Diagrams, “provide a means of detecting breaks in the consistency of precipitation records and, by referring to the station history, those breaks resulting from physical changes in the environment of the gauge can be identified.(1, p. 160)”

In the past, the Double–Mass Diagram has been used to check for consistency, therefore, Double-Mass Diagrams were developed to check the consistency of the First Order Weather Stations. However, according to J.P.

Bruce, author of Introduction to Hydrometeorology, this method of analysis is not suitable for the adjustment of daily or storm precipitation. (1, p. 160)"

5.2 RESULTING CURVES

Two sets of curves were developed based on the two methods for determining the Areas of Influence: Theissan Polygons and Similar Climatological Areas. Both sets of curves were plotted on semilog paper. To provide a table of values to be used in conjunction with the curves the following power function equation was used.

$$I_{RI} = A_o{*}T_c\text{^}(A_1+A_2{*}LOG_e(T_c)) \qquad (7)$$

5.2.1 First Set of Curves – First Order Stations Only

The first set of curves that were developed are similar to the curves that the State currently uses. These curves were developed based on Areas of Influence determined by Theissan Polygons. The Theissan Polygons were developed around First Order Weather Stations. Only three of the First Order Stations are located within Kentucky. Data from those stations were checked using the Double Mass Diagram Method. Tables 7-24 provide a list of the coefficients used in Equation 7 and the actual values produced for each return period and time of concentration. Figures 9-17 provide the graphs of the curves for each of the nine Areas of Influence.

Table 7. Coefficients Used In Equation 7 For Bristol Area.

Return Interval	A_0	A_1	A_2
2	33.67773	-0.883138	0.008029
5	25.35387	-0.617308	-0.018838
10	23.19608	-0.505112	-0.030187
25	21.90784	-0.402367	-0.040585
50	21.50471	-0.344413	-0.046452
100	21.38051	-0.297495	-0.051203

Table 8. IDF Curve Values Used For Bristol Area.

Return Period	2	5	10	25	50	100
15	3.268	4.150	4.734	5.472	6.019	6.562
60	1.036197	1.476474	1.767976	2.136286	2.40952	2.68073
1440	0.083653	0.105115	0.119324	0.137277	0.150595	0.163815

Figure 9. IDF Curve for Bristol Area.

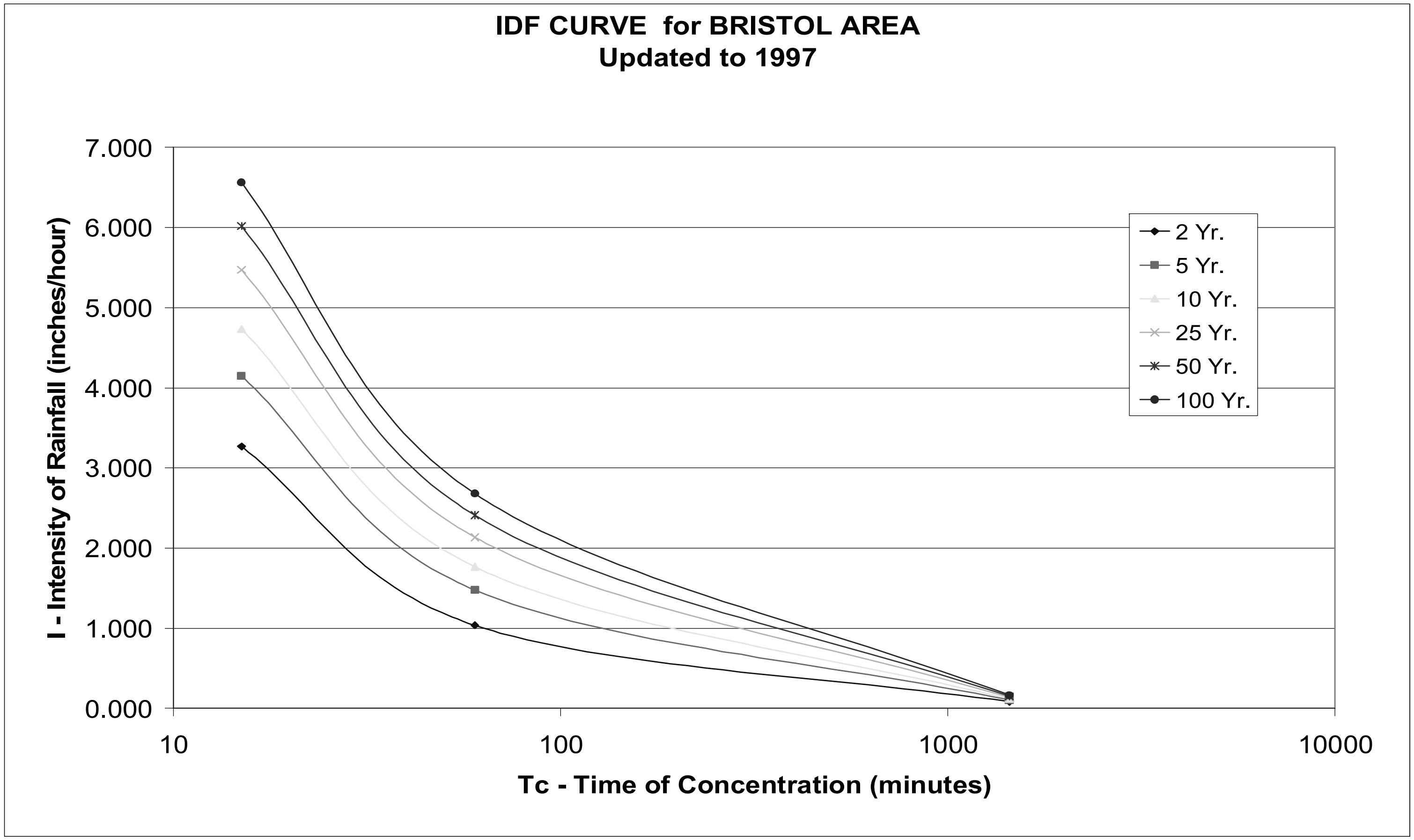


Table 9. Coefficients Used In Equation 7 For Cairo Area.

Return Interval	A_0	A_1	A_2
2	19.0321	-0.599823	-0.011112
5	74.69713	-1.053149	0.031284
10	134.0309	-1.236132	0.048487
25	232.2889	-1.400274	0.063961
50	319.9492	-1.491598	0.072588
100	417.736	-1.56493	0.079525

Table 10. IDF Curve Values Used For Cairo Area.

Return Period	2	5	10	25	50	100
15	3.457	5.424	6.727	8.373	9.594	10.806
60	1.355212	1.692028	1.91503	2.196791	2.405817	2.613295
1440	0.13483	0.184351	0.217138	0.258564	0.289296	0.319801

Figure 10. IDF Curve for Cairo Area.

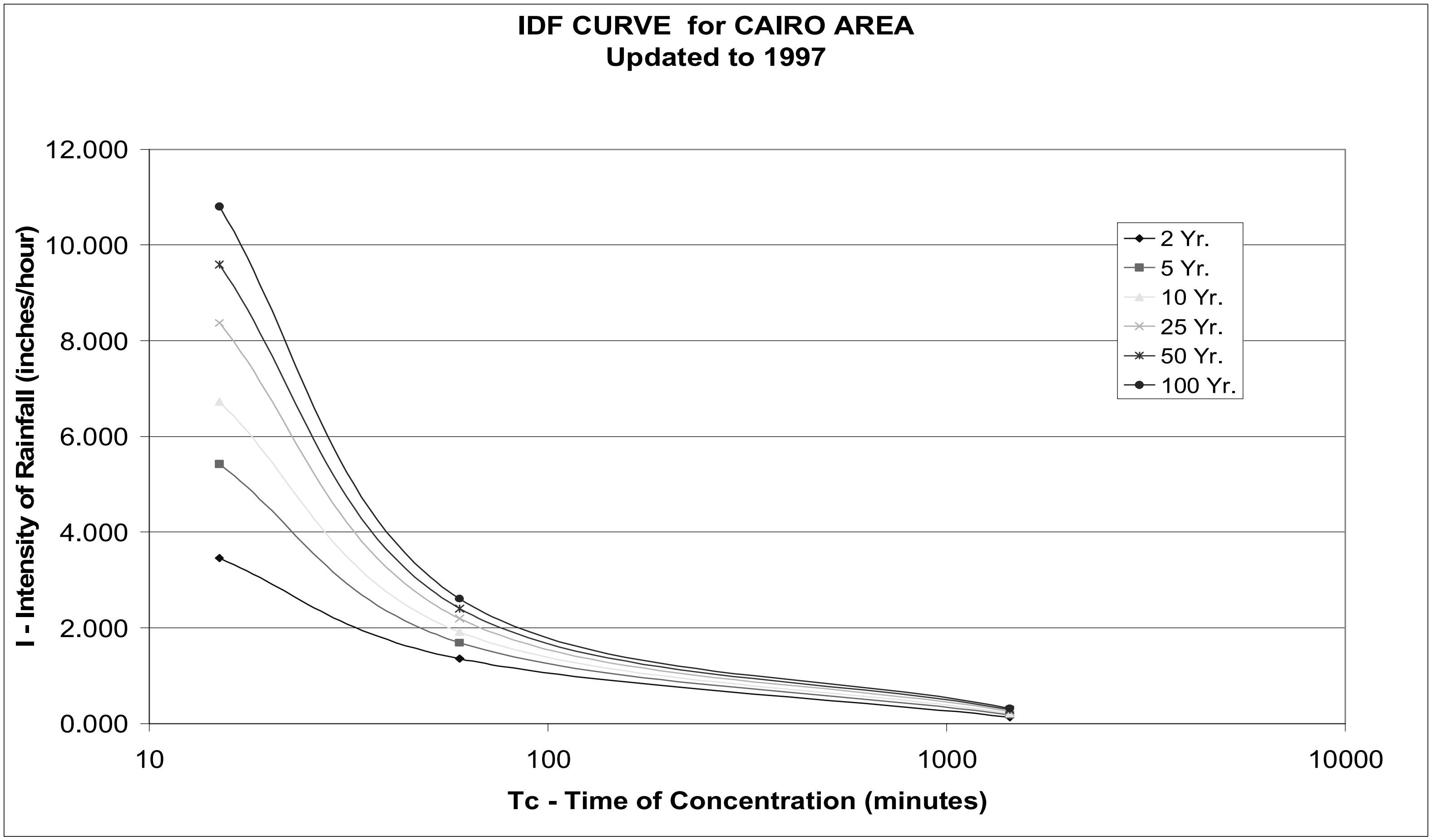


Table 11. Coefficients Used In Equation 7 For Cincinnati Area.

Return Interval	A_0	A_1	A_2
2	129.2053	-1.431498	0.065328
5	160.1754	-1.394745	0.06092
10	190.8523	-1.39927	0.060806
25	221.8911	-1.390168	0.059527
50	244.9198	-1.384973	0.058796
100	267.7791	-1.380735	0.0582

Table 12. IDF Curve Values Used For Cincinnati Area.

Return Period	2	5	10	25	50	100
15	4.323	5.732	6.740	7.957	8.860	9.756
60	1.100191	1.472486	1.718979	2.030419	2.261463	2.490796
1440	0.123194	0.158037	0.181106	0.210253	0.231876	0.253339

Figure 11. IDF Curve for Cincinnati Area.

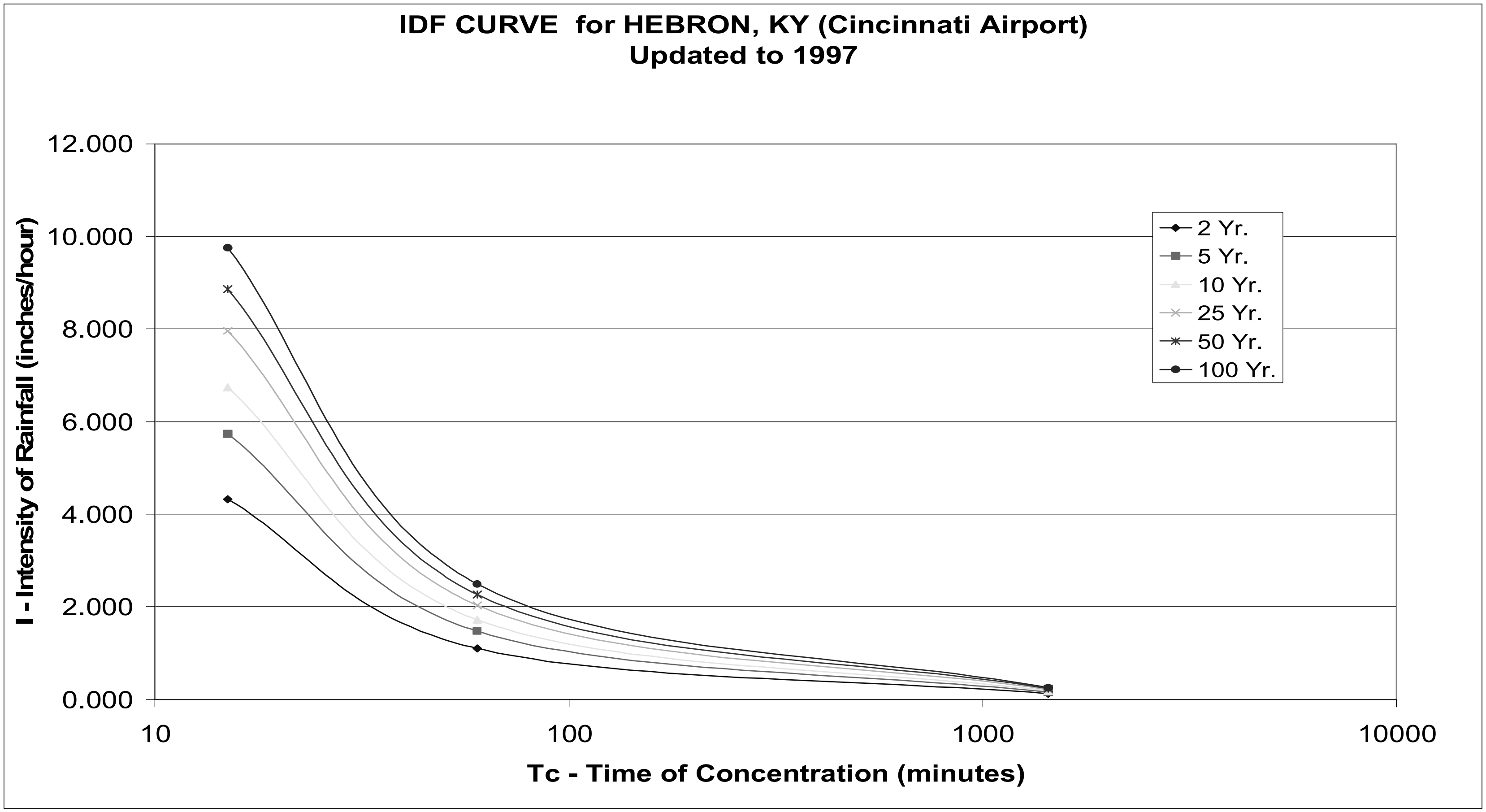


Table 13. Coefficients Used In Equation 7 For Evansville Area.

Return Interval	A_0	A_1	A_2
2	137.1378	-1.401048	0.058185
5	183.3746	-1.378498	0.054825
10	213.9496	-1.369067	0.05342
25	252.5583	-1.360486	0.052143
50	281.19	-1.355672	0.051426
100	309.6036	-1.35179	0.050848

Table 14. IDF Curve Values Used For Evansville Area.

Return Period	2	5	10	25	50	100
15	4.728	6.557	7.768	9.298	10.433	11.559
60	1.173518	1.626695	1.926739	2.30584	2.58708	2.866236
1440	0.111836	0.147506	0.171122	0.200961	0.223097	0.245069

Figure 12. IDF Curve for Evansville Area.

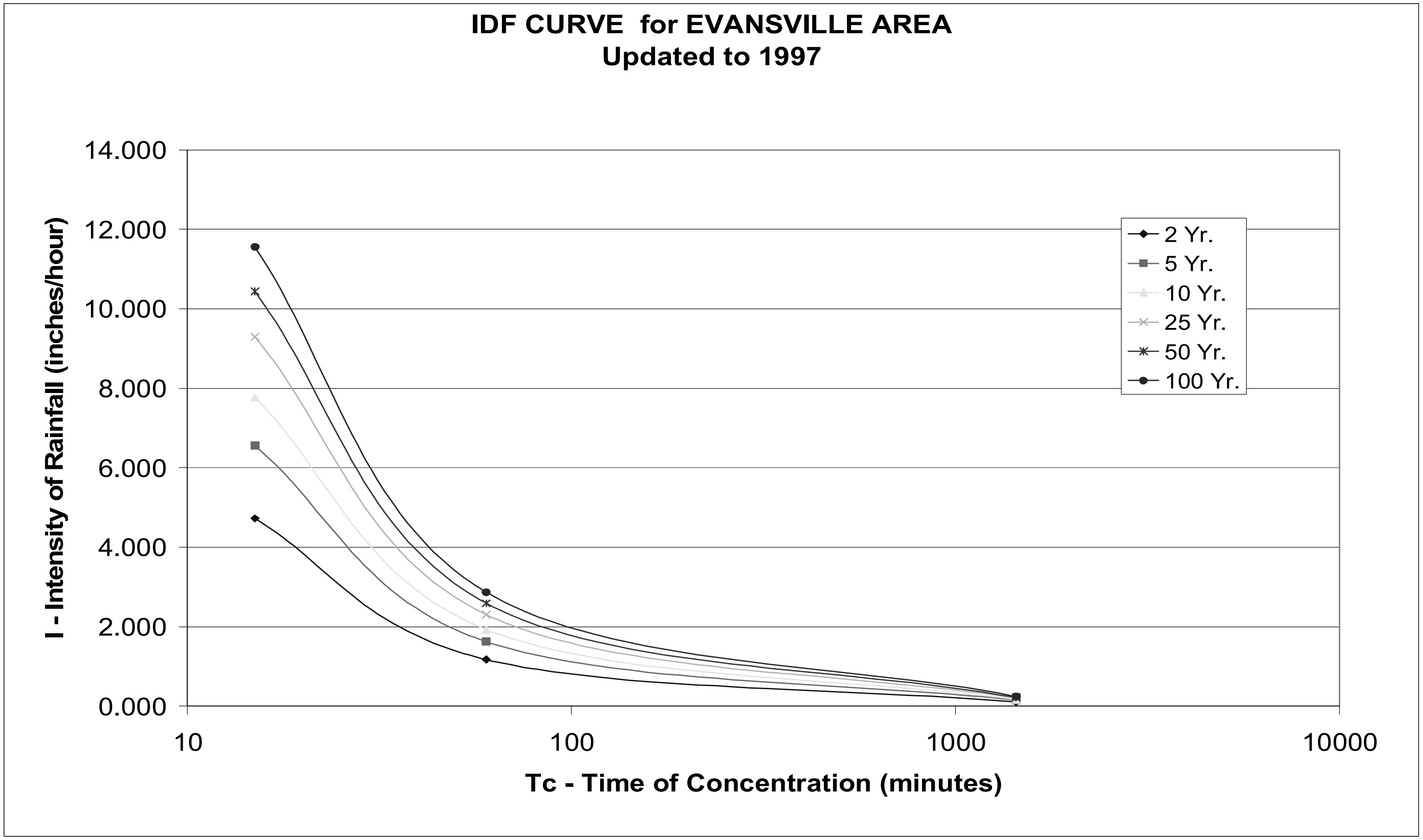


Table 15. Coefficients Used In Equation 7 For Huntington Area.

Return Interval	A_0	A_1	A_2
2	283.9637	-1.671855	0.078241
5	394.4177	-1.646155	0.072402
10	495.8392	-1.657456	0.071833
25	599.2254	-1.650562	0.069765
50	675.1657	-1.646119	0.068537
100	750.0877	-1.642231	0.06751

Table 16. IDF Curve Values Used For Huntington Area.

Return Period	2	5	10	25	50	100
15	5.448	7.772	9.436	11.444	12.933	14.412
60	1.122205	1.570204	1.866818	2.241588	2.519613	2.795579
1440	0.093333	0.114761	0.128947	0.146872	0.16017	0.173369

Figure 13. IDF Curve for Huntington Area.

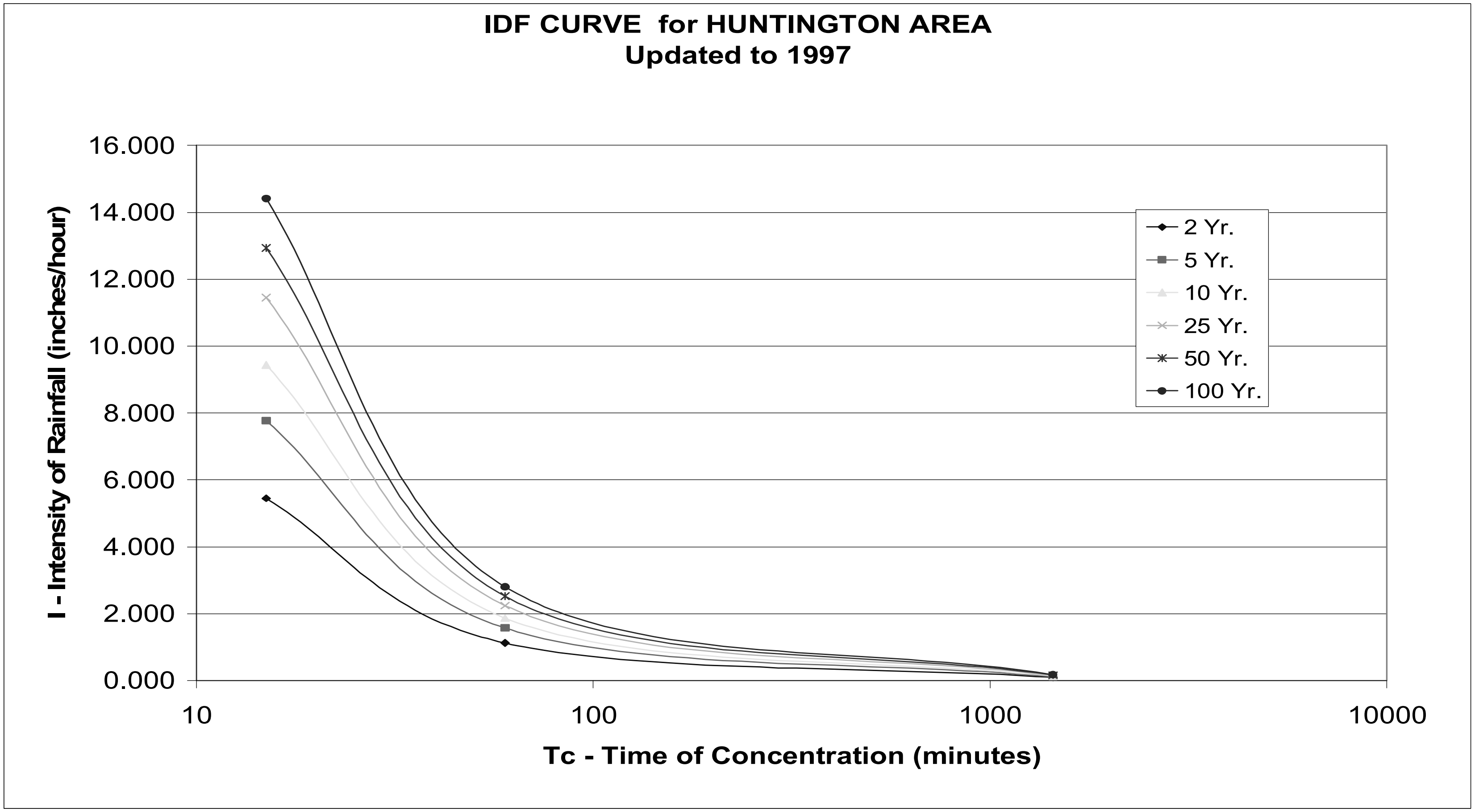


Table 17. Coefficients Used In Equation 7 For Knoxville Area.

Return Interval	A_0	A_1	A_2
2	154.7002	-1.488847	0.067409
5	218.9205	-1.492442	0.066538
10	261.334	-1.493566	0.066138
25	314.8533	-1.494399	0.065755
50	354.5233	-1.494788	0.065533
100	393.8795	-1.495062	0.06535

Table 18. IDF Curve Values Used For Knoxville Area.

Return Period	2	5	10	25	50	100
15	4.499	6.266	7.435	8.912	10.008	11.096
60	1.078594	1.482254	1.749513	2.087191	2.337701	2.586354
1440	0.108513	0.142865	0.165609	0.194346	0.215665	0.236825

Figure 14. IDF Curve for Knoxville Area.

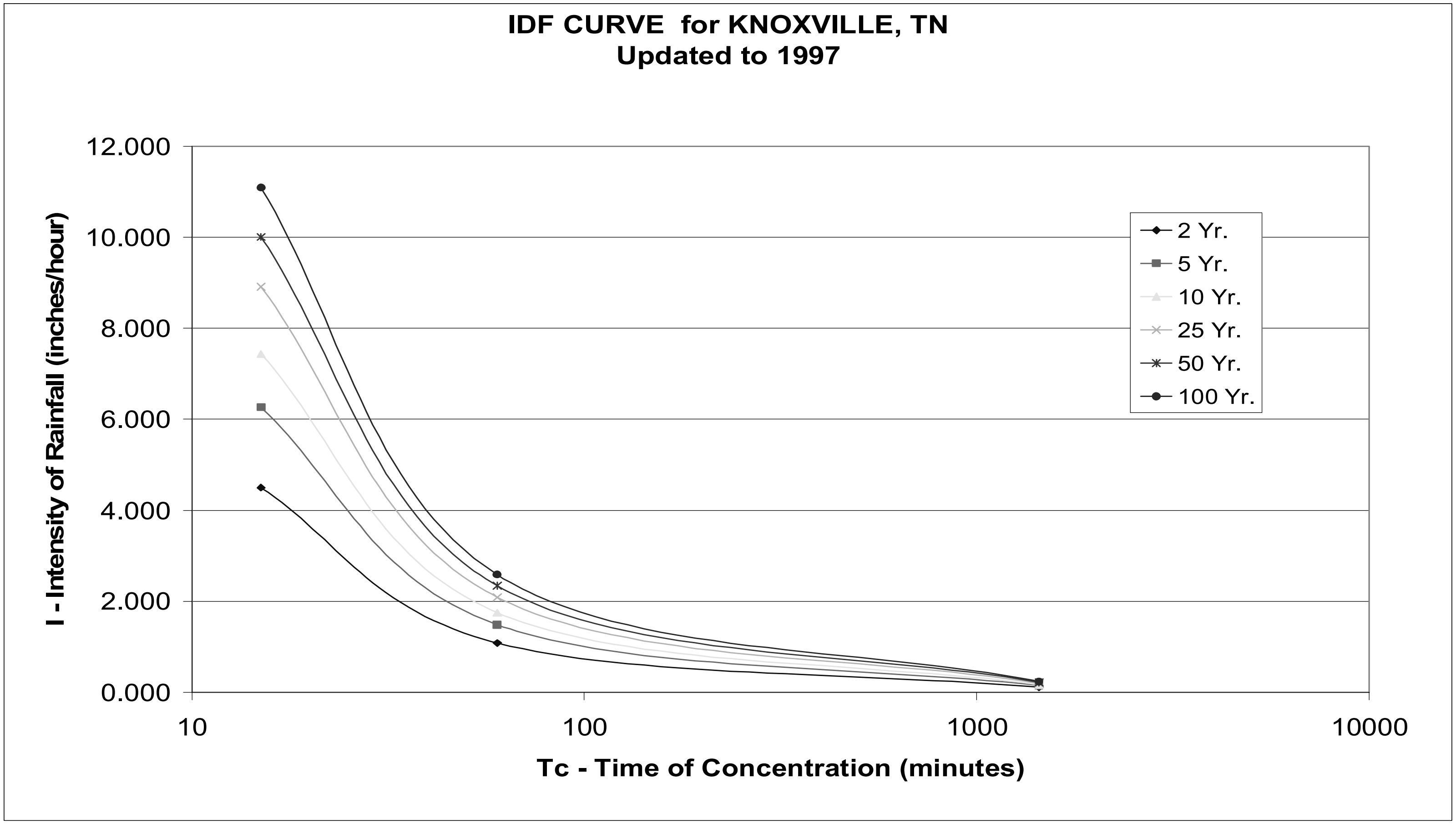


Table 19. Coefficients Used In Equation 7 For Lexington Area.

Return Interval	A_0	A_1	A_2
2	176.6497	-1.492869	0.065739
5	398.4551	-1.704175	0.084027
10	575.5811	-1.790704	0.091503
25	823.2727	-1.868603	0.098227
50	1019.936	-1.911986	0.101969
100	1223.487	-1.946817	0.104971

Table 20. IDF Curve Values Used For Lexington Area.

Return Period	2	5	10	25	50	100
15	5.020	7.307	8.821	10.733	12.152	13.561
60	1.178077	1.52	1.746383	2.032415	2.24461	2.455234
1440	0.110167	0.140597	0.160744	0.1862	0.205084	0.223829

Figure 15. IDF Curve for Lexington Area.

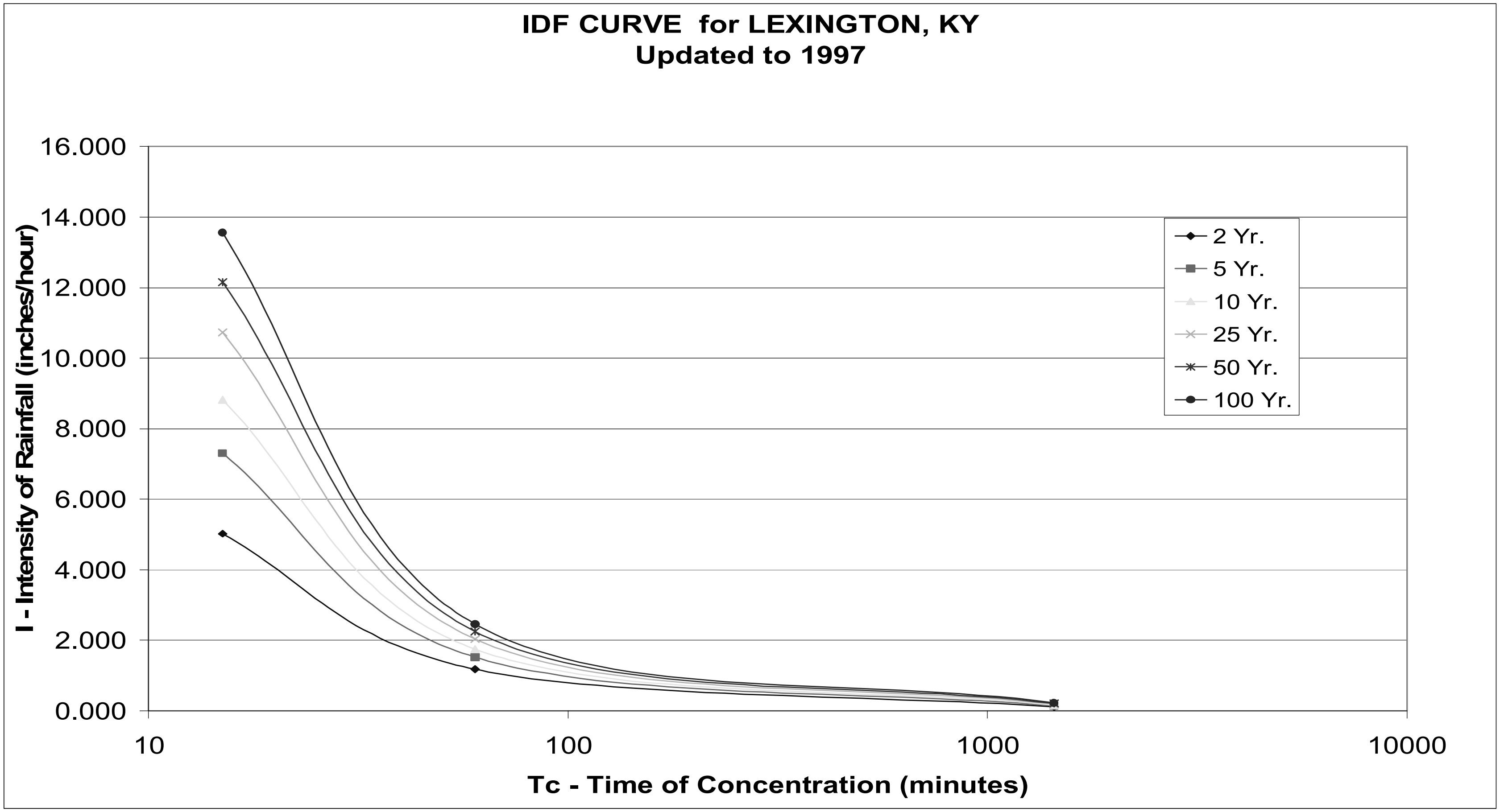


Table 21. Coefficients Used In Equation 7 For Louisville Area.

Return Interval	A_0	A_1	A_2
2	222.5488	-1.58724117	0.074312
5	414.144	-1.72080199	0.087237
10	552.7436	-1.77510646	0.092498
25	736.0492	-1.8237498	0.097214
50	1019.936	-1.91198645	0.101969
100	1223.487	-1.94681715	0.104971

Table 22. IDF Curve Values Used For Louisville Area.

Return Period	2	5	10	25	50	100
15	5.216	7.433	8.901	10.755	12.131	13.497
60	1.164365	1.55748	1.817756	2.146613	2.390578	2.632735
1440	0.109953	0.153451	0.182251	0.21864	0.245635	0.27243

Figure 16. IDF Curve for Louisville Area.

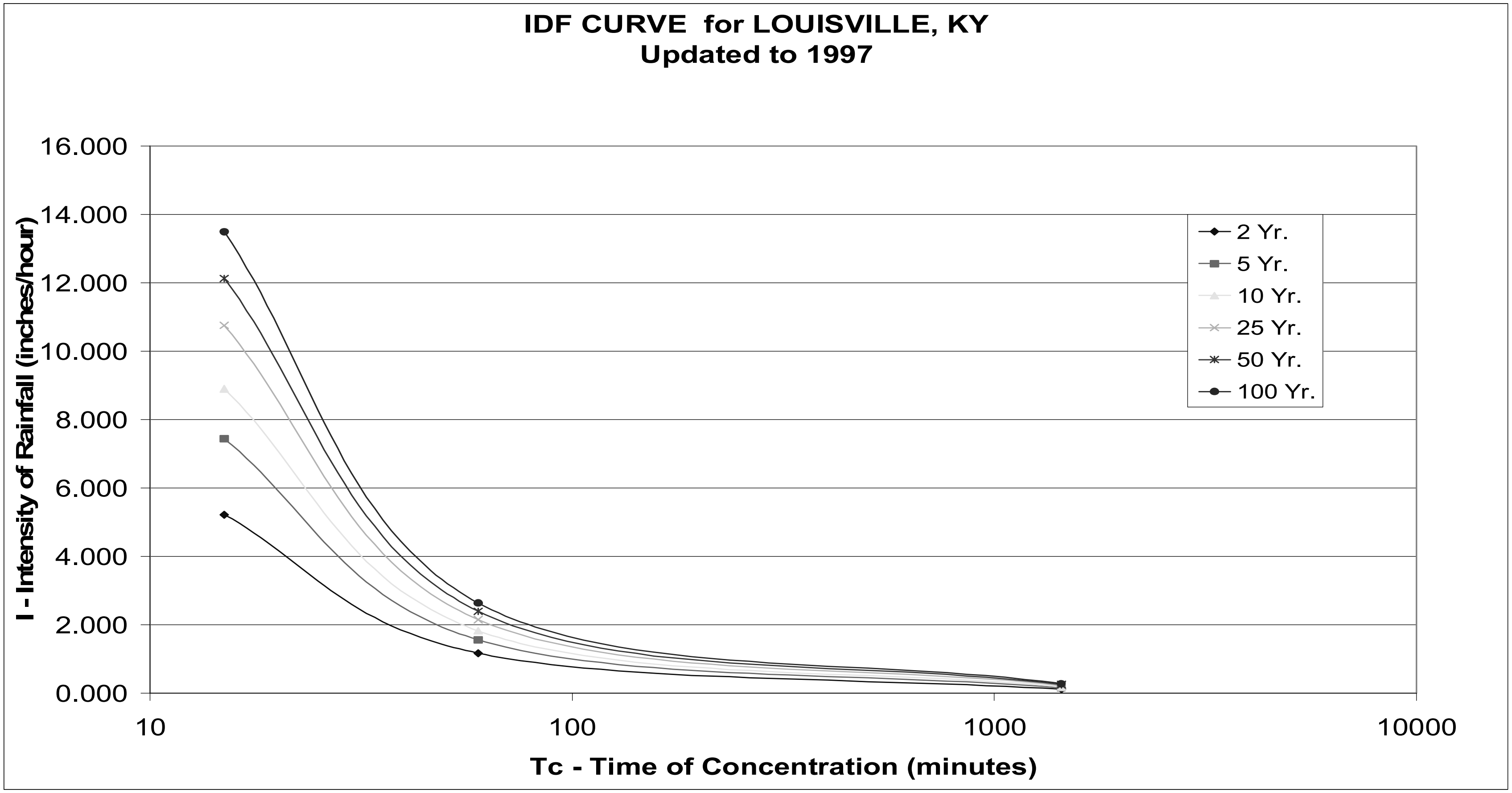


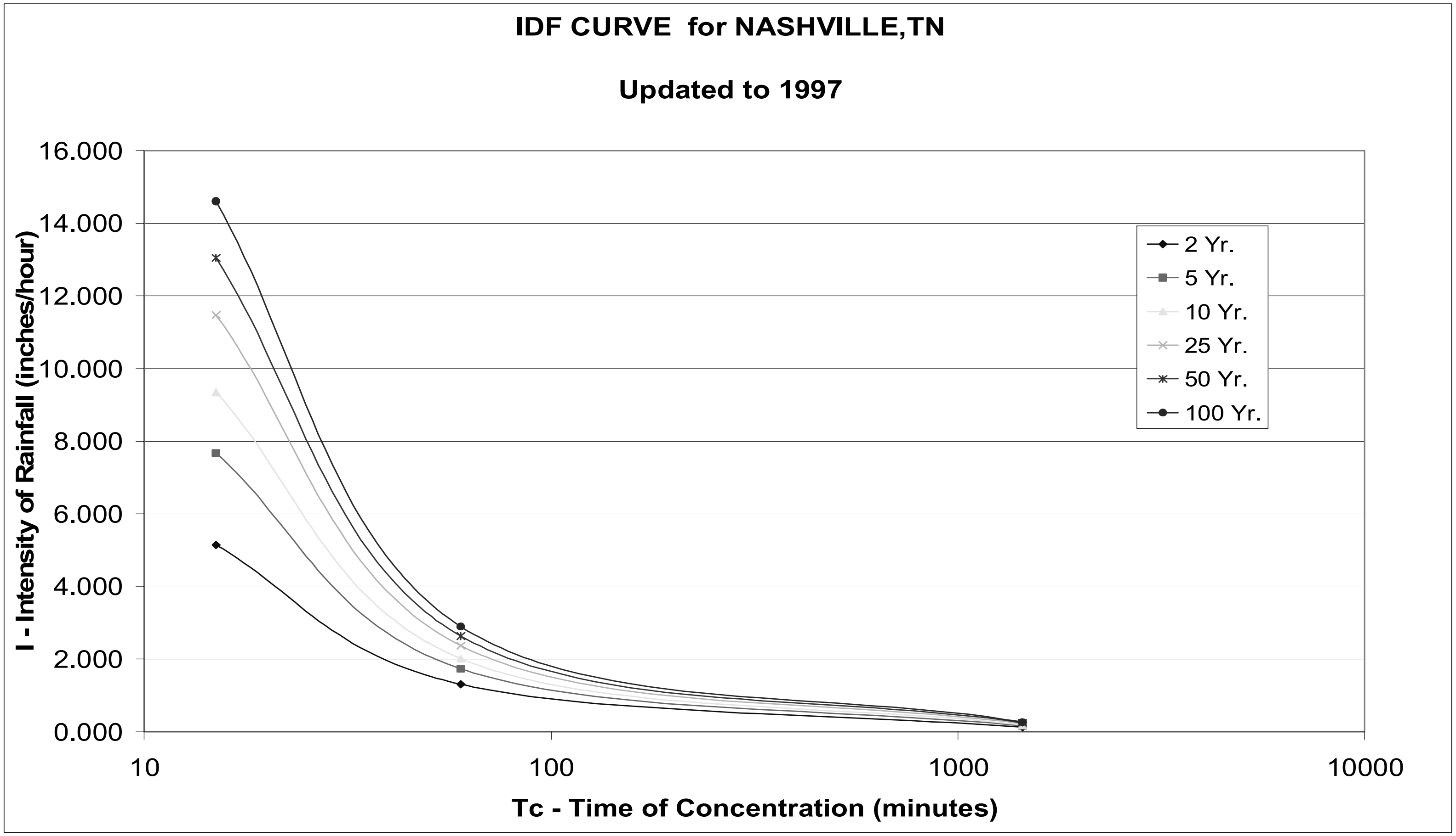
Table 23. Coefficients Used In Equation 7 For Nashville Area.

Return Interval	A_0	A_1	A_2
2	134.2828	-1.347742	0.052868
5	310.6287	-1.560134	0.07154
10	450.1371	-1.644154	0.078926
25	643.4977	-1.718388	0.085452
50	795.8918	-1.759164	0.089036
100	952.7959	-1.791612	0.091889

Table 24. IDF Curve Values Used For Nashville Area.

Return Period	2	5	10	25	50	100
15	5.144	7.678	9.355	11.474	13.046	14.607
60	1.307455	1.733509	2.015593	2.372004	2.636411	2.898858
1440	0.121807	0.161425	0.187655	0.220797	0.245383	0.269788

Figure 17. IDF Curve for Nashville Area.



5.2.2 Second Set of Curves – Similar Climatological Areas

The second set of curves are quite different from the first set of curves as their Areas of Influence are based on similar Climatological Zones. The data used to develop these curves comes only from within the state. The data used for these curves includes three First Order Stations and all the Co-Op Stations within the state. Tables 25-32 provide a list of the coefficients used in Equation 7 and the actual values produced for each return period and time of concentration. Figures 18-21 provide the graphs of the curves for each of the four areas of influence.

Table 25. Coefficients Used in Equation 7 for Bluegrass Area.

Return Interval	A_0	A_1	A_2
2	22.5285	-0.535569	-0.017977
5	46.05686	-0.75234	0.00283
10	65.53465	-0.853478	0.012559
25	93.84447	-0.951794	0.022029
50	117.1154	-1.009844	0.027626
100	141.8439	-1.058296	0.032301

Table 26. IDF Curve Values Used For Bluegrass Area.

Return Period	2	5	10	25	50	100
15	4.630	6.130	7.124	8.379	9.310	10.234
60	1.860075	2.218824	2.456347	2.756454	2.979092	3.20008
1440	0.177133	0.224973	0.256647	0.296667	0.326357	0.355826

Figure 18. IDF Curve for Bluegrass Area.

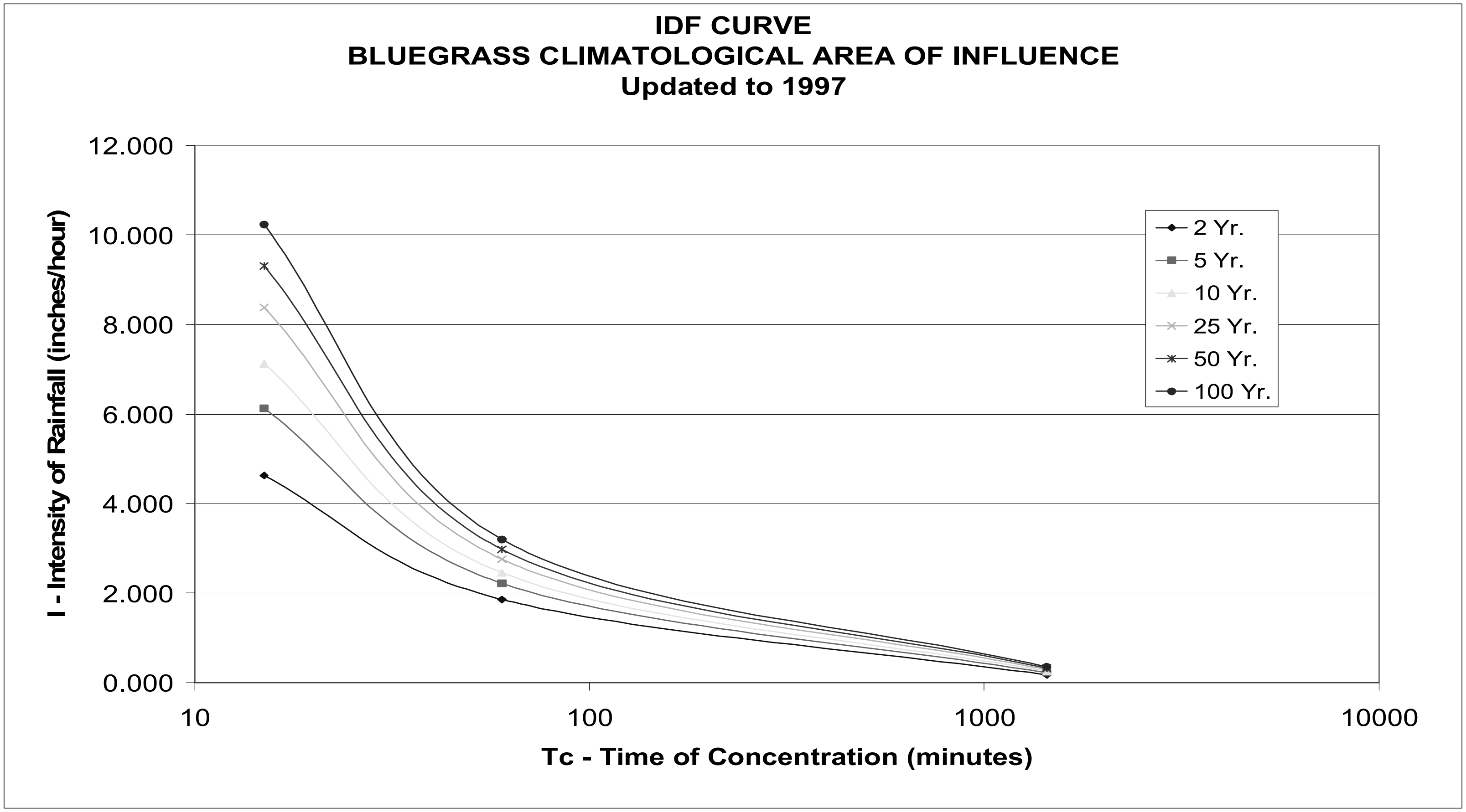


Table 27. Coefficients Used in Equation 7 for Central Area.

Return Interval	A_0	A_1	A_2
2	17.05755	-0.427042	-0.025626
5	36.32168	-0.653919	-0.003323
10	52.2187	-0.755906	0.006715
25	75.15205	-0.85279	0.016258
50	93.85382	-0.908976	0.021794
100	113.595	-0.955303	0.026361

Table 28. IDF Curve Values used For Central Area.

Return Period	2	5	10	25	50	100
15	4.447	6.033	7.083	8.409	9.393	10.370
60	1.931984	2.361613	2.646066	3.005468	3.272093	3.536744
1440	0.197042	0.26214	0.305241	0.359698	0.400098	0.440198

Figure 19. IDF Curve for Central Area.

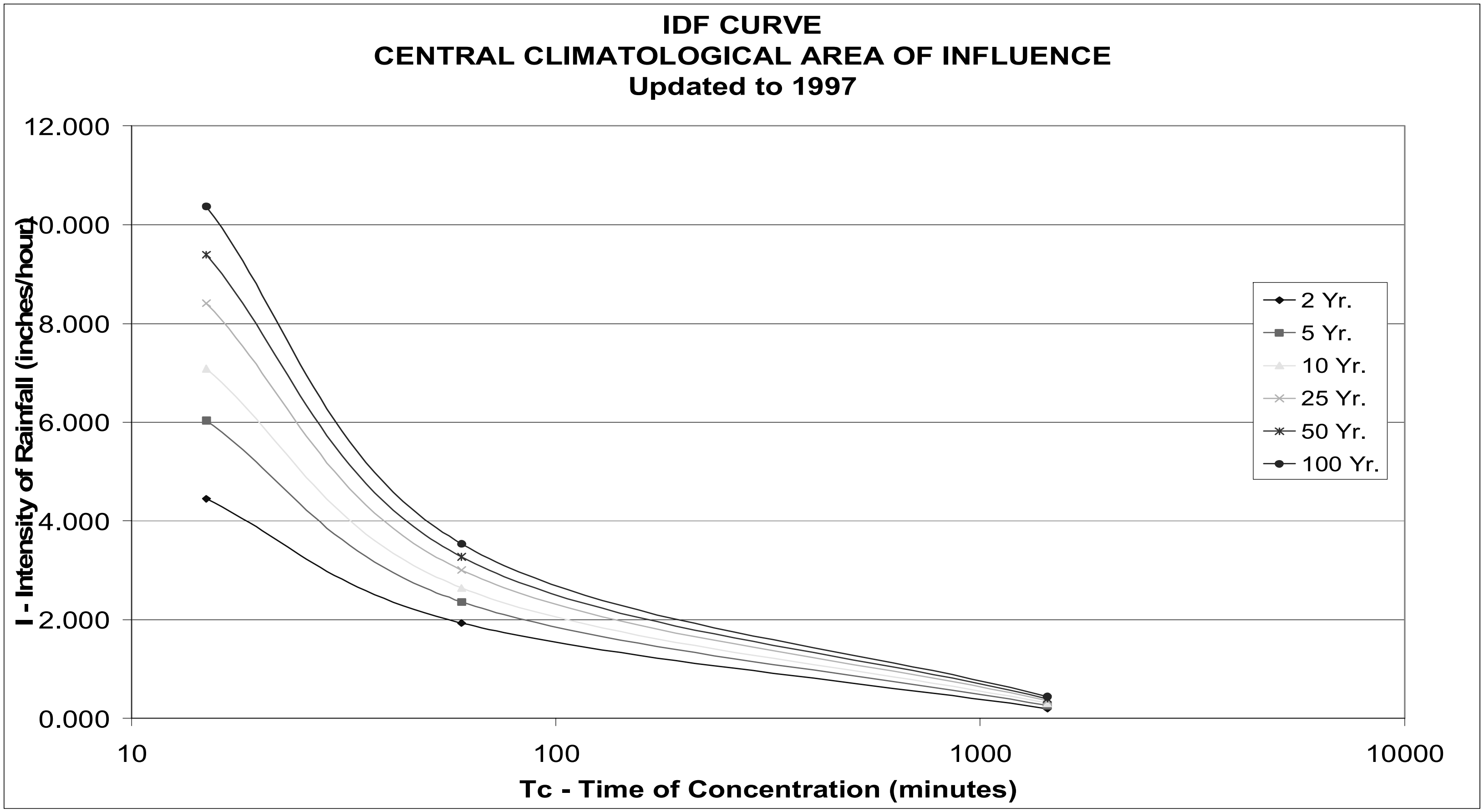


Table 29. Coefficients Used In Equation 7 for Eastern Area.

Return Interval	A_0	A_1	A_2
2	22.63798	-0.502789	-0.0232
5	53.12095	-0.778279	0.002854
10	80.55144	-0.906891	0.015055
25	122.6957	-1.032104	0.026958
50	158.8146	-1.106164	0.034009
100	198.3127	-1.16807	0.039909

Table 30. IDF Curve Values Used for Eastern Area.

Return Period	2	5	10	25	50	100
15	4.894	6.592	7.717	9.138	10.192	11.238
60	1.958386	2.302201	2.529836	2.817451	3.030821	3.24261
1440	0.171384	0.215141	0.244111	0.280716	0.307871	0.334825

Figure 20. IDF Cuve for Eastern Area.

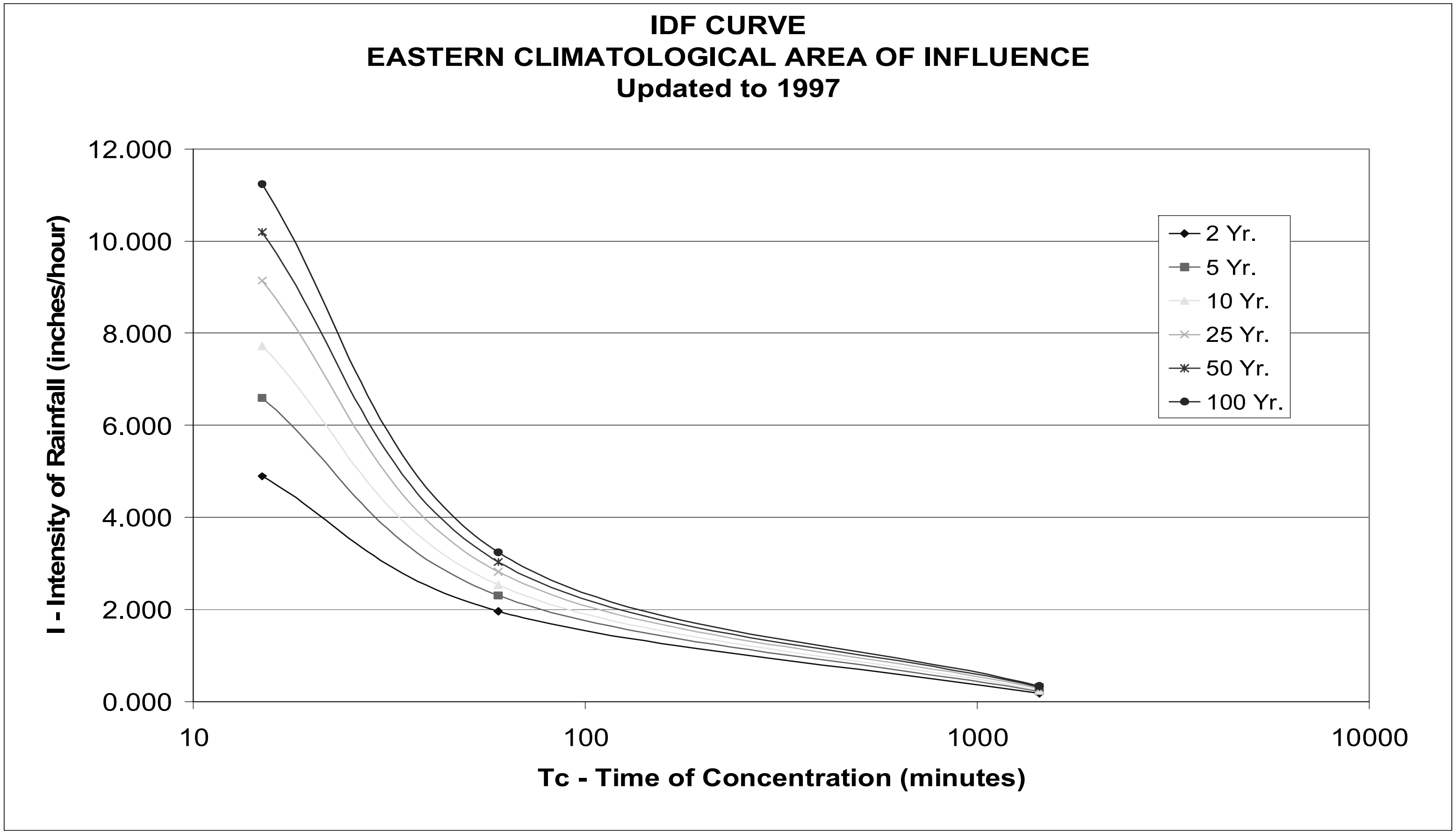


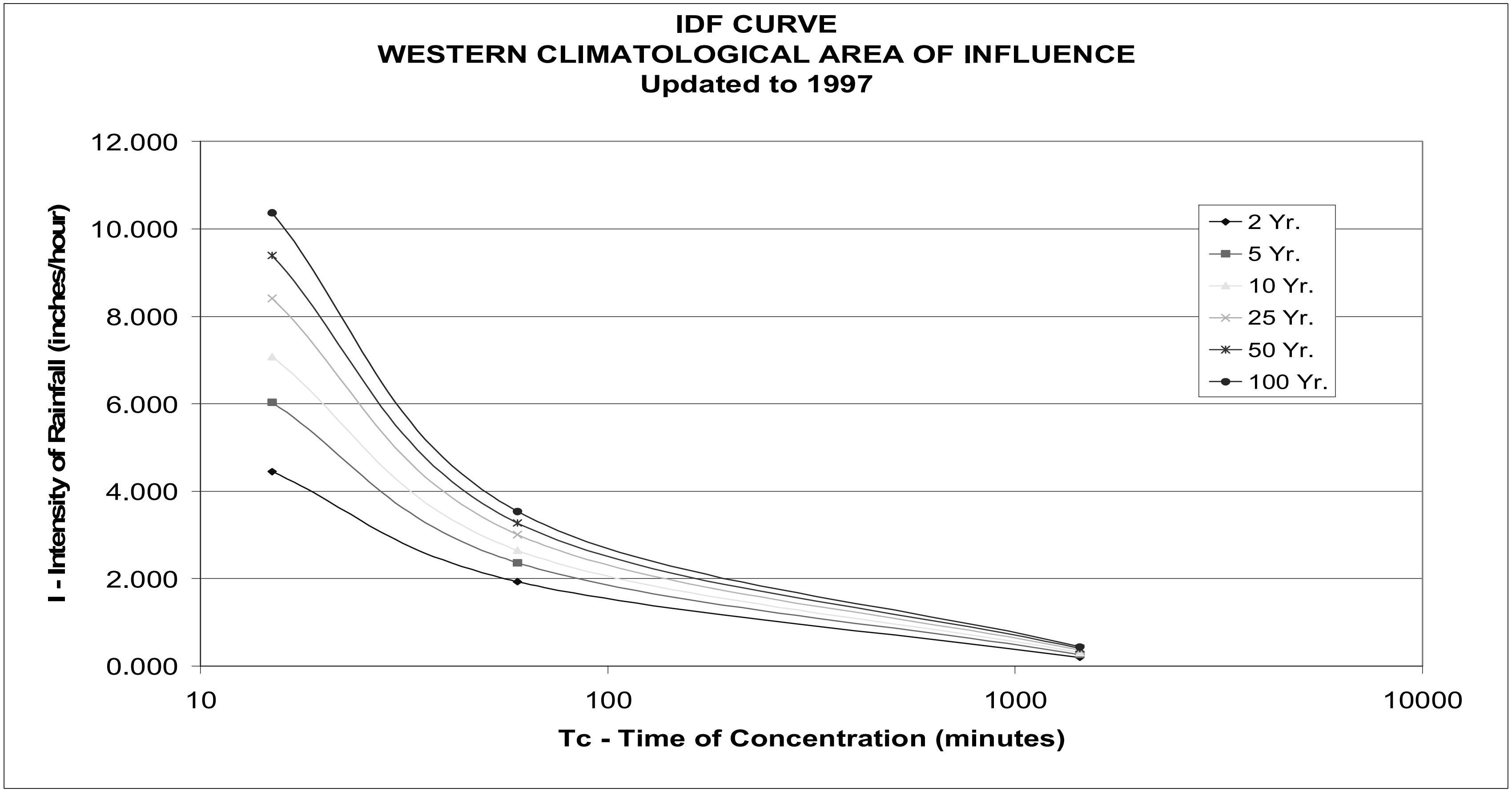
Table 31. Coefficients used in Equation 7 for Western Area.

Return Interval	A_0	A_1	A_2
2	17.05755	-0.427042	-0.025626
5	36.32168	-0.653919	-0.003323
10	52.2187	-0.755906	0.006715
25	75.15205	-0.85279	0.016258
50	93.85382	-0.908976	0.021794
100	113.595	-0.955303	0.026361

Table 32. IDF Curve Values Used for Western Area.

Return Period	2	5	10	25	50	100
15	4.447	6.033	7.083	8.409	9.393	10.370
60	1.931984	2.361613	2.646066	3.005468	3.272093	3.536744
1440	0.197042	0.26214	0.305241	0.359698	0.400098	0.440198

Figure 21. IDF Curve for Western Area.



6. FINAL RESULTS

At the Interim Meeting with the Study Advisory Committee it was decided to use IDF Curves determined by Similar Climatological Areas as the governing curves in Kentucky. However, the selected set of curves were extremely steep for short duration periods. As a result, linear regression had to be applied to the curves to produce usable values.

6.1 LINEAR REGRESSION

Using only 15-minute, hourly, and daily rainfall data produces Rainfall Intensity-Duration-Frequency (IDF) curves that are extremely steep and values for short periods of time are extremely inflated. Lagrangian interpolation seemed to be the natural choice as the available data was not evenly spaced. However, this method produced negative values because the difference between the 60-minute values and the 1440-minute values was so vast. To flatten out the IDF curve the existing points were plotted on a log lo graph and then linear regression was applied to approximate the values for the shorter time periods.

Linear Regression is a statistical tool used to predict unknown values using actual values. A Linear Regression trendline uses the least squares method to plot a straight line. In order to implement this statistical method, both the independent variable, rainfall duration (15-, 60-, 1440-minute), and the dependant variable, rainfall intensity, are mathematically manipulated. The natural log of the rainfall durations, is calculated and then squared, thus creating two sets of values. The natural log is also calculated for the rainfall intensity, thus creating a third set of values. Those three sets of values are then used in Microsoft Excel's Data Analysis Tool Package, Linear Regression program, to calculate the three coefficients for the following equation.

$$\text{Intensity of Rainfall} = e^{\,C1 + C2*\ln(\text{duration}) + C3*(\ln(\text{duration}))^{\wedge}2} \qquad (7)$$

Once the numerical coefficients are determined, rainfall intensity for any duration can be determined. Points can then be calculated for the 5-, 10-, 15-, 20-, 30-, 80-, 100-, 120-minute intervals by plugging those values into the equation. Table 33 lists the coefficients for each area and each return period within that area.

TABLE 33. Coefficients to be used with Final Curves.

BLUEGRASS AREA						
	RETURN					
	2-Yr	5-Yr	10-Yr	25-Yr	50-Yr	100-Yr
C_1	3.11478	3.82988	4.18258	4.54164	4.76316	4.95473
C_2	-0.5356	-0.7523	-0.8535	-0.9518	-1.0098	-1.0583
C_3	-0.018	0.00283	0.01256	0.02203	0.02763	0.0323
CENTRAL AREA						
	RETURN					
	2-Yr	5-Yr	10-Yr	25-Yr	50-Yr	100-Yr
C_1	2.83668	3.59261	3.95563	4.31933	4.5415	4.73248
C_2	-0.4271	-0.654	-0.756	-0.8527	-0.9089	-0.9552
C_3	-0.0256	-0.0033	0.00672	0.01625	0.02179	0.02636
EASTERN AREA						
	RETURN					
	2-Yr	5-Yr	10-Yr	25-Yr	50-Yr	100-Yr
C_1	3.12008	3.97246	4.38902	4.80983	5.06778	5.28974
C_2	-0.503	-0.7782	-0.9069	-1.0322	-1.1062	-1.168
C_3	-0.0232	0.00285	0.01506	0.02696	0.03401	0.0399
WESTERN AREA						
	RETURN					
	2-Yr	5-Yr	10-Yr	25-Yr	50-Yr	100-Yr
C_1	3.70048	4.20285	4.45448	4.71303	4.87478	5.01583
C_2	-0.7765	-0.8911	-0.9434	-0.9931	-1.0222	-1.0461
C_3	0.00682	0.01773	0.02271	0.02745	0.03022	0.03251

There is a different equation for each return period within a particular area. The resulting six equations per area can be used for discharge calculations. For convenience, values have been calculated for the Bluegrass, Central, Eastern and Western Areas of the Commonwealth and are included in Tables 34-37. The Rainfall Intensity Duration Frequency Curves for each area follow and are listed as Figures 22-25. These graphs are similar in nature to the graphs generated in previous years, pitting Rainfall Intensity against Time of Concentration.

6.2 BLUEGRASS CLIMATOLOGICAL AREA RESULTS

Listed below are the six equations for the Bluegrass Climatological Area. The values generated from those equations are listed in Table 34. Figure 22 shows the graph of the IDF curves for the Bluegrass Area.

2 Year Return Period: $I = e^{3.114781 - 0.53557*\ln(duration) - 0.01798*(\ln(duration))^2}$ (8)

5 Year Return Period: $I = e^{3.829877 - 0.75234*\ln(duration) + 0.00283*(\ln(duration))^2}$ (9)

10 Year Return Period: $I = e^{4.182579 - 0.85348*\ln(duration) + 0.012559*(\ln(duration))^2}$ (10)

25 Year Return Period: $I = e^{4.541639 - 0.95179*\ln(duration) + 0.022029*(\ln(duration))^2}$ (11)

50 Year Return Period: $I = e^{4.76316 - 1.00984*\ln(duration) + 0.027626*(\ln(duration))^2}$ (12)

100 Year Return Period: $I = e^{4.954727 - 1.0583*\ln(duration) + 0.032301*(\ln(duration))^2}$ (13)

Table 34. Values for the Bluegrass Climatological Area.

VALUES FOR BLUEGRASS CLIMATOLOGICAL AREA						
	RETURN PERIOD					
Tc	2-Yr	5-Yr	10-Yr	25-Yr	50-Yr	100-Yr
5	9.081599	13.8234	17.14128	21.47405	24.76514	28.08213
10	5.967187	8.269335	9.815452	11.7852	13.25502	14.71939
15	4.630192	6.130374	7.123627	8.37859	9.309595	10.2337
20	3.853673	4.960292	5.688769	6.606221	7.285324	7.958457
30	2.960164	3.683108	4.157908	4.755152	5.196883	5.634521
60	1.860075	2.218824	2.456347	2.756454	2.979092	3.20008
80	1.526086	1.799382	1.981332	2.211891	2.383261	2.553559
100	1.306231	1.529955	1.679518	1.869438	2.010797	2.151388
120	1.148796	1.340331	1.468741	1.632037	1.753693	1.874754
1440	0.177133	0.224973	0.256647	0.296667	0.326357	0.355826

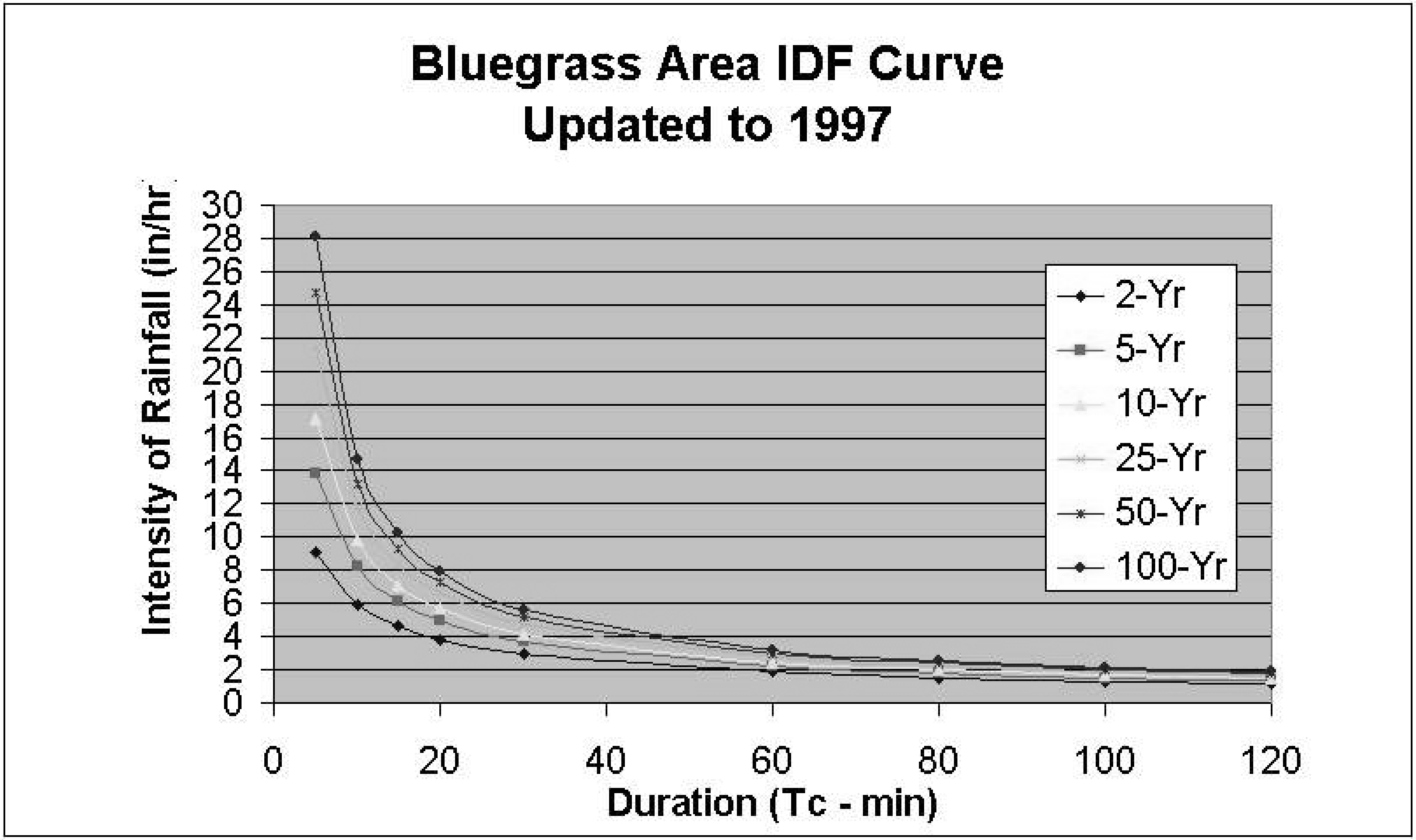


Figure 22. Graph of the IDF Curves for the Bluegrass Climatological Area after Linear Regression.

6.3 CENTRAL CLIMATOLOGICAL AREA RESULTS

Listed below are the six equations for the Central Climatological Area. The values generated from those equations are listed in Table 35. Figure 23 shows the graph of the IDF curves for the Central Area.

2 Year Return Period: $I = e^{2.83668 - 0.42708*\ln(duration) - 0.02562*(\ln(duration))^2}$ (8)

5 Year Return Period: $I = e^{3.592611 - 0.65399*\ln(duration) + 0.00332*(\ln(duration))^2}$ (9)

10 Year Return Period: $I = e^{3.955634 - 0.75598*\ln(duration) + 0.006722*(\ln(duration))^2}$ (10)

25 Year Return Period: $I = e^{4.319334 - 0.85272*\ln(duration) + 0.016252*(\ln(duration))^2}$ (11)

50 Year Return Period: $I = e^{4.541499 - 0.90888*\ln(duration) + 0.021786*(\ln(duration))^2}$ (12)

100 Year Return Period: $I = e^{4.732482 - 0.95524*\ln(duration) + 0.026356*(\ln(duration))^2}$ (13)

Table 35. Values for the Central Climatological Area.

VALUES FOR CENTRAL CLIMATOLOGICAL AREA						
	RETURN PERIOD					
Tc	2-Yr	5-Yr	10-Yr	25-Yr	50-Yr	100-Yr
5	8.028175	12.57184	15.74217	19.86636	22.99183	26.13687
10	5.570311	7.918115	9.493096	11.4964	12.99057	14.47886
15	4.447	6.033	7.083	8.409	9.393	10.37
20	3.770936	4.971198	5.761773	6.757524	7.495055	8.226471
30	2.967439	3.78062	4.315254	4.988124	5.486169	5.979872
60	1.931984	2.361613	2.646066	3.005468	3.272093	3.536744
80	1.605128	1.940831	2.164053	2.446724	2.656703	2.865287
100	1.386134	1.666177	1.852935	2.089787	2.265884	2.4409
120	1.227248	1.470519	1.633052	1.83937	1.992847	2.145428
1440	0.197042	0.26214	0.305241	0.359698	0.400098	0.440198

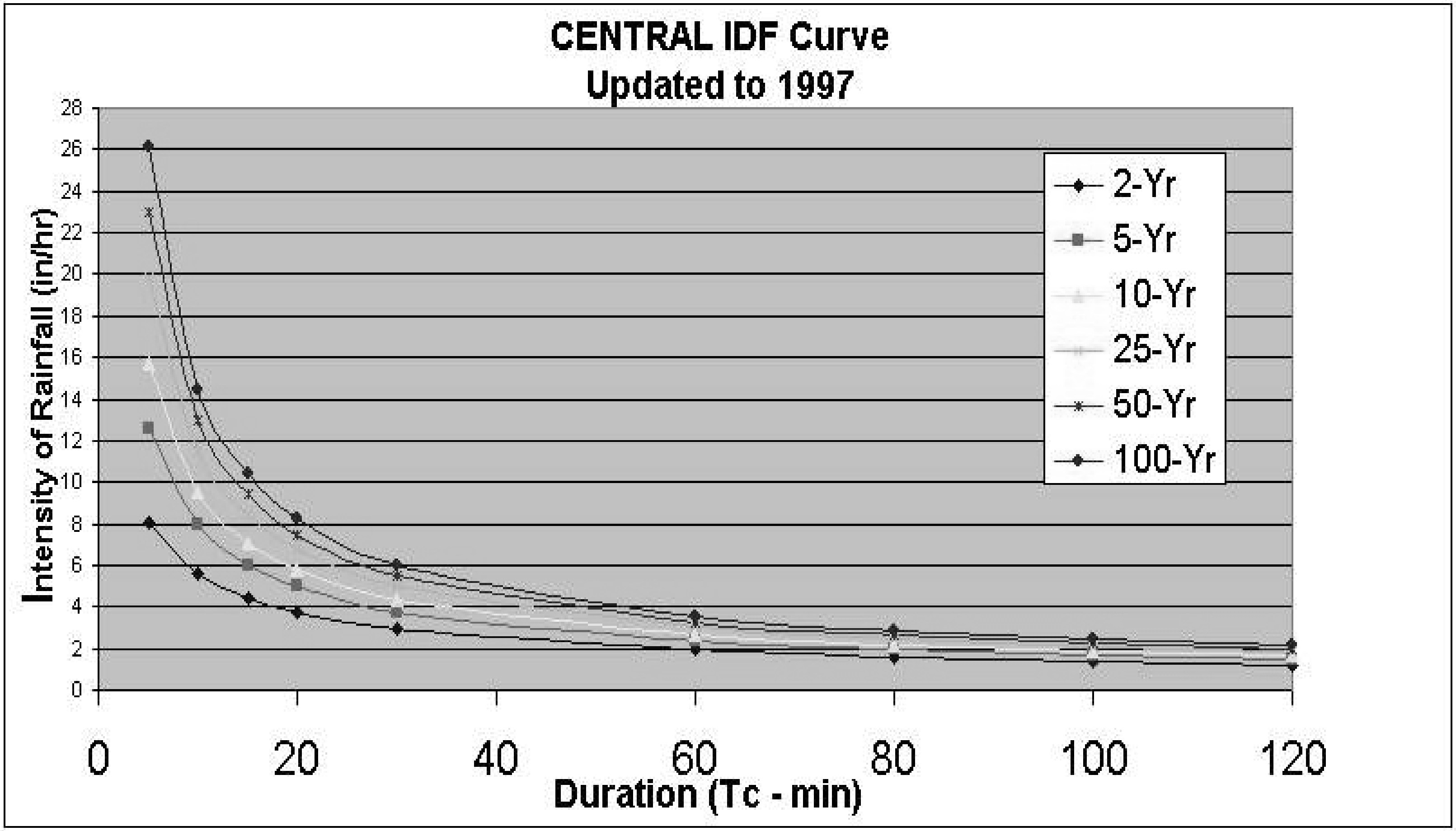


Figure 23. Graph of the IDF Curves for the Central Climatological Area after Linear Regression.

6.4 EASTERN AREA RESULTS

Listed below are the six equations for the Eastern Climatological Area. The values generated from those equations are listed in Table 36. Figure 24 shows the graph of the IDF curves for the Eastern Area.

2 Year Return Period: $I = e^{3.120085 - 0.50296*\ln(duration) - 0.02318*(\ln(duration))^2}$ (8)

5 Year Return Period: $I = e^{3.972464 - 0.77824*\ln(duration) + 0.00285*(\ln(duration))^2}$ (9)

10 Year Return Period: $I = e^{4.389025 - 0.90694*\ln(duration) + 0.01506*(\ln(duration))^2}$ (10)

25 Year Return Period: $I = e^{4.809834 - 1.03215*\ln(duration) + 0.026962*(\ln(duration))^2}$ (11)

50 Year Return Period: $I = e^{5.067777 - 1.10618*\ln(duration) + 0.03401*(\ln(duration))^2}$ (12)

100 Year Return Period: $I = e^{5.289735 - 1.16803*\ln(duration) + 0.039905*(\ln(duration))^2}$ (13)

Table 36. Values for the Eastern Climatological Area.

VALUES FOR EASTERN CLIMATOLOGICAL AREA						
	RETURN PERIOD					
Tc	2-Yr	5-Yr	10-Yr	25-Yr	50-Yr	100-Yr
5	9.49288	15.29186	19.46017	24.99031	29.24026	33.55655
10	6.29054	8.985526	10.81098	13.14663	14.89497	16.64023
15	4.894	6.592	7.717	9.138	10.192	11.238
20	4.076641	5.294392	6.093523	7.097564	7.839552	8.574213
30	3.130537	3.890322	4.386601	5.008733	5.467809	5.921959
60	1.958386	2.302201	2.529836	2.817451	3.030821	3.24261
80	1.601421	1.85323	2.021758	2.23591	2.395374	2.554013
100	1.366377	1.566724	1.701977	1.874612	2.003525	2.131987
120	1.198126	1.366124	1.480271	1.626435	1.735802	1.844917
1440	0.171384	0.215141	0.244111	0.280716	0.307871	0.334825

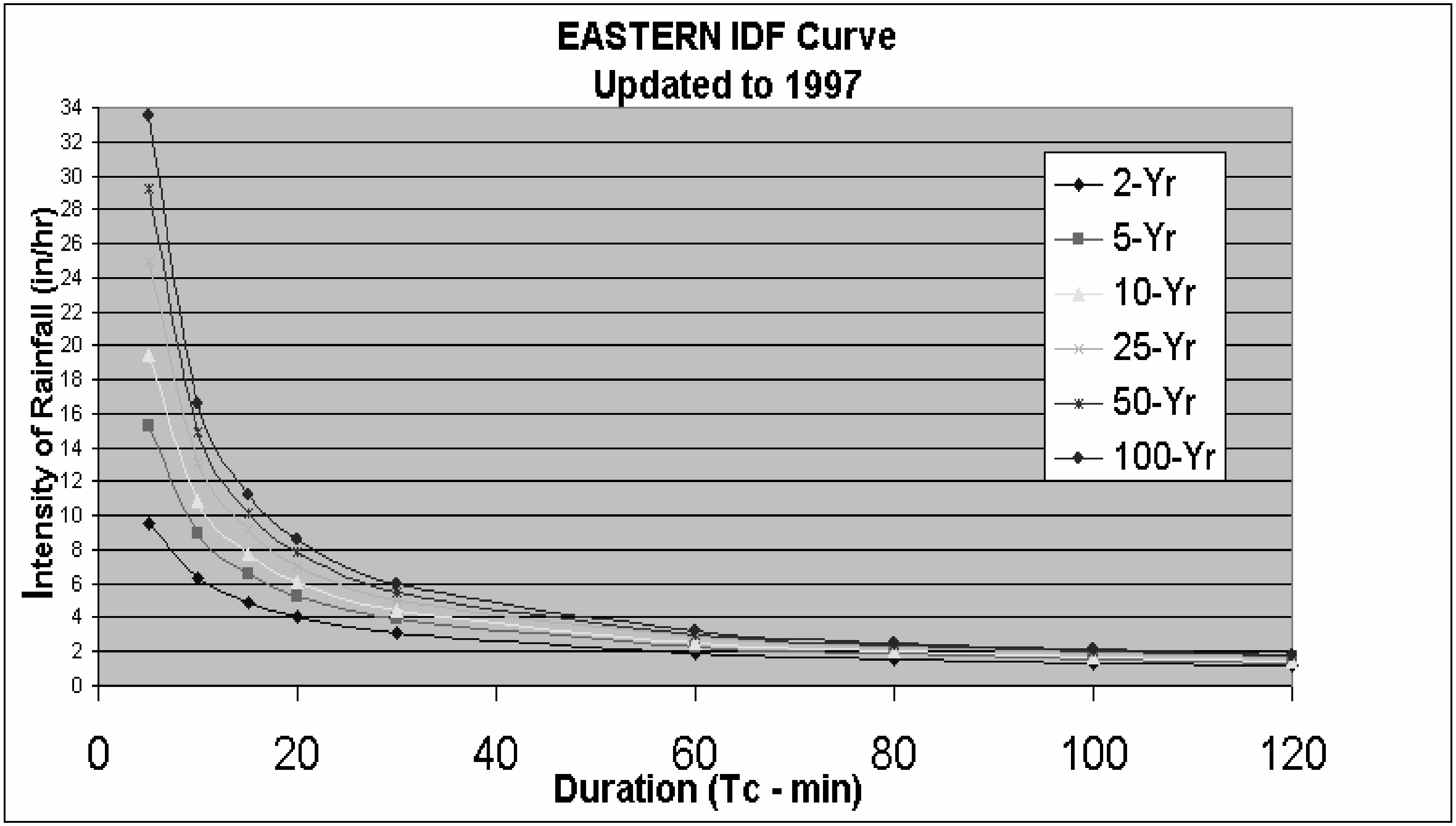


Figure 24. Graph of the IDF Curves for the Eastern Climatological Area after Linear Regression.

6.4WESTERN AREA RESULTS

Listed below are the six equations for the Western Climatological Area. The values generated from those equations are listed in Table 37. Figure 25 shows the graph of the IDF curves for the Western Area.

2 Year Return Period: $I = e^{3.114781 - 0.53557*\ln(duration) - 0.01798*(\ln(duration))^2}$ (8)

5 Year Return Period: $I = e^{3.829877 - 0.75234*\ln(duration) + 0.00283*(\ln(duration))^2}$ (9)

10 Year Return Period: $I = e^{4.182579 - 0.85348*\ln(duration) + 0.012559*(\ln(duration))^2}$ (10)

25 Year Return Period: $I = e^{4.541639 - 0.95179*\ln(duration) + 0.022029*(\ln(duration))^2}$ (11)

50 Year Return Period: $I = e^{4.76316 - 1.00984*\ln(duration) + 0.0827626*(\ln(duration))^2}$ (12)

100 Year Return Period: $I = e^{4.954727 - 1.0583*\ln(duration) + 0.032301*(\ln(duration))^2}$ (13)

Table 37. Values for the Western Climatological Area.

VALUES FOR WESTERN CLIMATOLOGICAL AREA						
	RETURN PERIOD					
Tc	2-Yr	5-Yr	10-Yr	25-Yr	50-Yr	100-Yr
5	11.80371	16.68652	19.98435	24.18632	27.32927	30.45981
10	7.019428	9.440484	11.05198	13.09002	14.60553	16.11028
15	5.195	6.819	7.895	9.253	10.261	11.261
20	4.201765	5.432762	6.246946	7.273886	8.035617	8.79113
30	3.121626	3.963462	4.519846	5.221677	5.74208	6.258269
60	1.888091	2.343293	2.644677	3.025472	3.307967	3.588371
80	1.535438	1.89351	2.130861	2.431007	2.653749	2.87492
100	1.308949	1.608239	1.806796	2.058032	2.244525	2.429747
120	1.149508	1.409213	1.581608	1.799832	1.961849	2.122787
1440	0.20479	0.261841	0.299613	0.347338	0.382743	0.417886

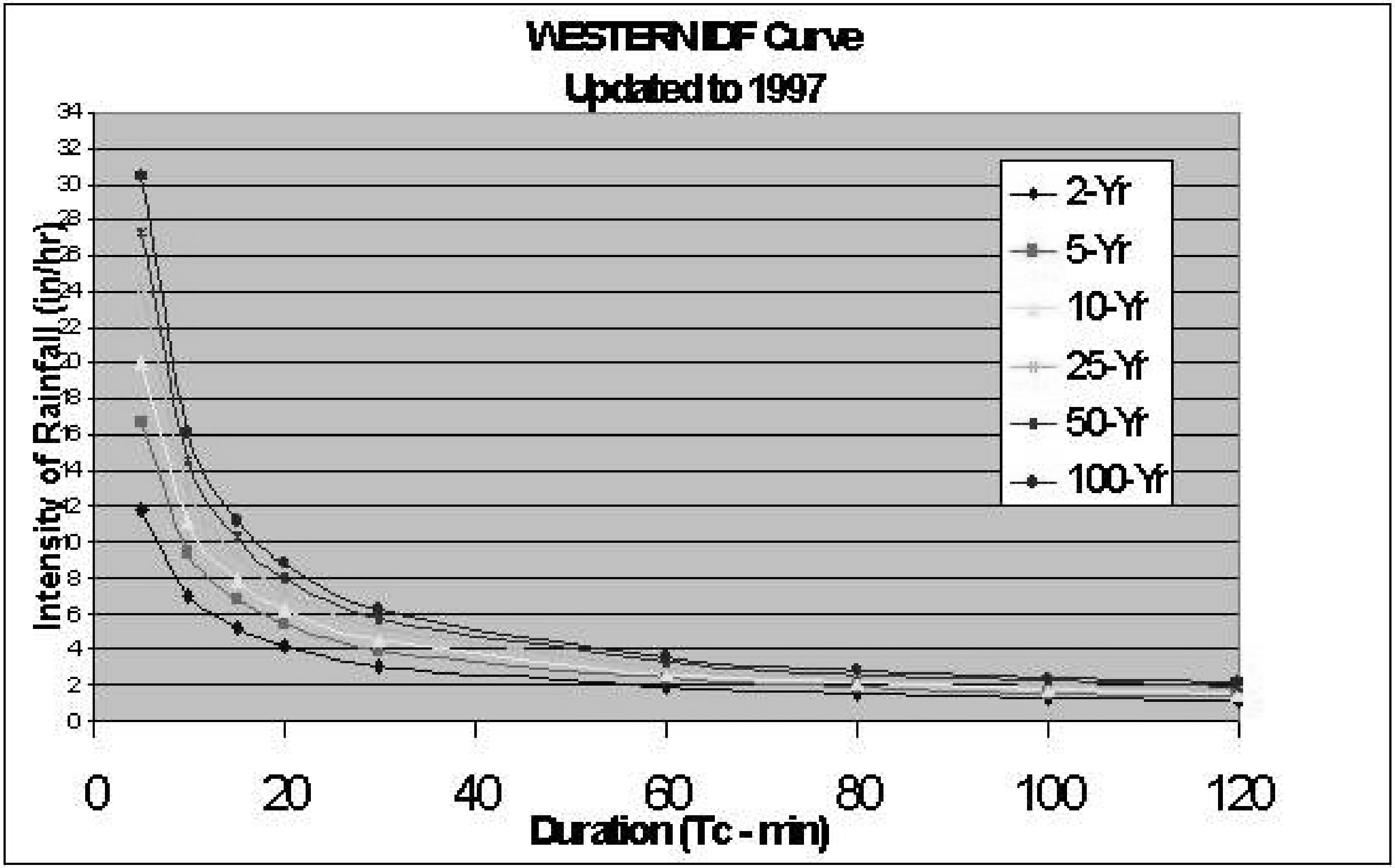


Figure 25. Graph of the IDF Curves for the Western Climatological Area after Linear Regression.

7.0 **SUMMARY**

The purpose of this study was to revise and update the already existing Rainfall Intensity Duration Frequency Curves (IDF) for the Commonwealth of Kentucky. When constructing an engineering project that must consider storm run-off, the Kentucky Transportation Cabinet uses the IDF Curves as an aid when designing drainage structures. The curves allow the engineer to design safe and economical flood control measures.

During the course of this project, it was determined that two major revisions in the procedures were necessary. The first revision was to change the way the Areas of Influence were determined. Areas determined by Thiessen Polygons were replaced with Areas determined by similar Climatological Areas. This change is in accordance with Bulletin 71 put out by the NOAA. Only data within the Commonwealth of Kentucky was used. This new procedure made use of data taken from Cooperative Weather Stations as well as First Order Stations. Thus, the data used to generate the curves was all local data and there were only four Areas of Influence established.

The second procedural change was in the amount of data and the way the data was collected. Previously, the State Climatologist supplied data for 5-, 10-, 15-, 20-, 30-, 45-, 60-, 80-, 100-, and 120-minute time intervals. However, First Order Stations no longer collect data for all those time periods; now they only collect hourly data. Some Cooperative Climate Stations do collect data for multiple time intervals, but they are few and far between. Once the data was collected analysis began. However, due to limited funding on this project, only the data from the First Order Weather stations was checked for consistency using the Double –Mass Diagram method.

Data was analyzed using the Gumbel Distribution Equation and then because there was limited data for short rainfall durations, some data had to be generated mathematically using Linear Interpolation.

These procedures produced the necessary values to generate four sets of curves. They are included in this report along with the curve equations. This is a vast change from the previous nine curves based on First-Order Weather Stations.

Funding for this project came from the Kentucky Transportation Cabinet under Research Study KYSPR 98-178, entitled “Revision of Rainfall Intensity-Duration Curves for Kentucky”.

REFERENCES

1. Bruce, J. P., Clark, R. H. Introduction to Hydrometeorology. Pergamon Press, Toronto, Canada, 1966.

2. Clark, K. D. Kentucky Department of Highways, Division of Research, Report No. 250, "Application of Standford Watershed Model Concepts to Predict Flood Peaks for Small Drainage Areas", 1968.

3. Dewberry, Sidney and Davis. Land Development Handbook: Planning, Engineering, and Surveying. McGraw-Hill Company, 1996.

4. EarthInfo CD² Reference Manual. EarthInfo, Inc. Boulder, CO. 1996

5. Frederick, Ralph H., Myers, Vance A., Auciello, Eugene P. "Five- to 60-Minute Precipitation Frequency for the Eastern and Central United States", NOAA Technical Memorandum NWS HYDRO-35, Silver Spring, MD 6/77.

6. http: // bader.engr.ucf.edu/research/leaglin/chap1.htm

7. http://wwwagwx.ca.ukky.edu/agwx/usr/weather/webdoc1.htm

8. http://www.uky.edu/KentuckyAtlas

9. http://www.uky.edu/KentuckyAtlas/phys-bluegrass.html

10. http://www.uky.edu/KentuckyAtlas/phys-eastern.html

11. http://www.uky.edu/KentuckyAtlas/phys-mississippi-embyment.html

12. http://www.uky.edu/KentuckyAtlas/phys-western-coal-field.html

13. Huff, Floyd A. and James R. Angel. "Rainfall Frequency Atlas of the Midwest" Bulletin 71, Midwestern Climate Center Research Report 92-03, 1993.

14. Kennoy Engineering, Inc. "Drainage Design Criteria and Procedures Manual", Lexington-Fayette Urban County Government, 1/85.

15. Kreyszig, Erwin. Advanced Engineering Mathematics, fourth edition. John Wiley & Sons. 1979.

16. Linsley, Jr. Ray K., Kohler, Max A., Paulhus, Joseph L. H. Hydrology for Engineers, 1st Ed., 1958, 2nd Ed. 1975, 3rd Ed. 1982, McGraw-Hill, 1975.

17. Mays, Jessie. Study KYP-56, “Updated Rainfall Intensity Duration Curves. 1985.

18. Wall, Larry and Randal L. Schwartz. Programming Perl. O’Reilly & Associates, Inc. Sebastopol, CA. 1991.

19. West, E. M. , Sammons, W. H. , Research Report No. 2, “A Survey of Runoff from Small Drainage Areas and the Opening in Attendant Drainage Structures.”, , Kentucky Department of Highways. July 1955.