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**STATISTICAL ANALYSIS OF INDIANA
RAINFALL DATA**

**A. Ramanchandra Rao
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April 2006

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16. Abstract <p>The basic objectives of research presented in this report are characterizing and modeling short time increment (hourly) rainfall data from Indiana. Characteristics of hourly rainfall data from Indiana were investigated. Data from 74 stations were used in the study.</p> <p>The homogeneity of Indiana hourly rainfall data was tested as a part of the study. Indiana hourly rainfall data is found to be statistically homogeneous. Several probability distributions were evaluated. Surprisingly, both the type I extreme value as well as the generalized extreme value distributions were found to be acceptable to characterize Indiana hourly rainfall data. The generalized extreme value distribution was used in this study.</p> <p>The intensity-duration-frequency relationships for Indiana were investigated next. Relationships are developed so that rainfall depth for any location in Indiana can be accurately estimated for specified durations and frequencies.</p> <p>There are several methods and procedures which have been developed to estimate rainfall depths. Results from these methods were compared to the results from in-situ data analysis. The results of this analysis are used to recommend the methods to use for rainfall estimation in Indiana.</p> <p>Huff curves were developed for all the stations and analyzed. Although stations in the state were divided into three groups as north, central and south, the Huff curves from the three regions were very close to each other. Consequently, a single set of Huff curves is recommended for use for the state of Indiana.</p>			
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Abstract

Several aspects of short time interval rainfall data from Indiana are investigated in this study. The goodness of fit of different probability distributions is considered first. Intensity-duration-frequency relationships are considered next. Information about estimation of rainfall intensities for different durations and frequencies in Indiana are presented next. The variability in rainfall intensity estimates by different procedures is quantified. Finally it is demonstrated that a single set of Huff curves may be used for the entire state to derive rainfall hyetographs.

I. Introduction

Rainfall intensities of various frequencies and durations are the basic inputs in hydrologic design. They are used, for example, in the design of storm sewers, culverts and many other structures as well as inputs to rainfall-runoff models. Precipitation frequency analysis is used to estimate rainfall depth at a point for a specified exceedence probability and duration.

In the United States, precipitation data are published in *Climatological Data and Hourly Precipitation Data* by the National Oceanic and Atmospheric Administration (NOAA) through the National Climatic Data Center (NCDC). The availability and interpretation of United States Rainfall data are discussed in NRC (1988). There are other national, regional and state agencies which also publish precipitation data. Stations which submit data to NCDC are expected to operate standard equipment and follow standard procedures and observation times (WB-ESSA, 1970). The data, however, may be erroneous due to wind effects, changes in station environment and observers and other factors. Hence, the data must be carefully examined before analysis.

(a) Rainfall Frequency Analysis

Rainfall frequency analysis is usually based on annual maximum series at a site (at-site analysis) or from several sites (regional analysis). Rainfall data are usually published at fixed time intervals such as clock hours; they may not always yield the true maximum amount for a specified duration. For example, the true annual maximum daily values are about, on the average, thirteen percent higher than the annual maximum daily values (Hershfield, 1961). Adjustment factors such as those in WMO (1983) are used with the results of a frequency analysis of annual maximum series. Many of these

adjustment factors have been established more than fifty years ago. They may also vary locally. Hence, these adjustment factors should be examined to test their validity.

(b) Results of Frequency Analysis

Data from about 4000 stations in the U.S. were analyzed by Hershfield (1961) to provide extended rainfall frequency information for the U.S. The resulting Rainfall Frequency Atlas is known as TP-40. The Gumbel distribution was used to generate point frequency maps for durations ranging from 30- min. to 24 h. and recurrence intervals from 10 to 100 years. Rainfall maps for durations of 2 to 10 days were published by the U.S. Weather Bureau in a publication called TP-49 (U.S. Weather Bureau (1964)). Later, Frederick et al. (1977) published isohyetal maps for durations from 5 to 60 min. in a publication known as HYDRO-35. The rainfall depths of 6 to 24 hr. for the Western United States was published in NOAA Atlas 2 by Miller et al. (1973). If sufficiently long data are available for a site, a frequency analysis can be performed. Gumbel, log-Pearson (III) and Generalized Extreme Value (GEV) distributions are commonly used in the frequency analysis. The GEV distribution with $k < 0$ is the standard distribution used in the Great Britain (NERC, 1975).

Recently the Midwest Climate Center has published the intensity-duration-frequency (IDF) atlas for midwestern United States (Huff and Angel, 1992). Indiana is included in this atlas. The Midwestern Climate Center is recommending the use of this atlas for design. Purdue et al. (1992) published the IDF and Huff curves for four first order meteorologic stations in Indiana. NOAA has updated the Intensity-duration-frequency (IDF) information for many parts of the U.S. This information (in draft form) is presently available on the World Wide Web site <http://hdsc.nws.nova.gov/hdsc/pfds>.

Comparison of IDF Information

Figure 1.1. Comparison of IDF Information

Return Period	T = 10 years					T = 100 years				
Duration (hr)	NOAA	LC	UC	Purdue	Huff	NOAA	LC	UC	Purdue	Huff
0.083	0.57	0.52	0.62	0.517		0.8	0.72	0.87	0.757	
0.5	1.5	1.36	1.63	1.432		2.16	1.96	2.34	2.097	
1	1.9	1.73	2.07	1.541	1.76	2.89	2.61	3.13	2.374	2.9
2	2.28	2.07	2.45	1.995	2.15	3.49	3.15	3.74	3.075	3.36
3	2.44	2.21	2.64	2.245	2.38	3.75	3.38	4.05	3.460	3.9
6	2.88	2.6	3.14	2.642	2.7	4.49	4	4.88	4.071	4.6
12	3.29	2.99	3.59	3.012	3.2	5.13	4.58	5.56	4.642	5.2
24	3.74	3.45	4.04	3.377	3.75	5.71	5.17	6.13	5.204	5.9
48	4.21	3.95	4.48	3.751	3.9	6.27	5.82	6.65	5.781	6.3

Return Period	T = 10 years					T = 100 years				
Duration (hr)	NOAA	LC	UC	Purdue	Huff	NOAA	LC	UC	Purdue	Huff
0.083	0.59	0.55	0.64	0.555		0.84	0.76	0.9	0.831	
0.5	1.57	1.44	1.69	1.321		2.26	2.05	2.43	1.978	
1	1.99	1.84	2.15	1.630	1.85	3.02	2.75	3.24	2.508	3.25
2	2.4	2.19	2.6	2.011	2.35	3.71	3.34	4.01	3.095	3.98
3	2.59	2.38	2.79	2.230	2.52	4.03	3.64	4.33	3.431	4.3
6	3.06	2.8	3.34	2.602	3.1	4.85	4.35	5.25	4.004	4.7
12	3.52	3.22	3.82	2.988	3.5	5.56	4.98	6	4.598	5.9
24	4.06	3.73	4.4	3.403	4	6.22	5.63	6.72	5.236	6.7
48	4.59	4.31	4.87	3.858	4.25	6.87	6.37	7.28	5.937	7.1

Comparison of IDF Information

Figure 1.1. Comparison of IDF Information (cont'd.)

Although there are several sources of IDF information, there may be considerable discrepancies in these results. The results for 10-year and 100-year recurrence intervals are presented in Figs. 1.1 and 1.2 for Indianapolis, Evansville, Fort Wayne and South Bend for different durations. The rainfall depths for different durations obtained by the latest NOAA results along with the upper (UC) and lower (LC) confidence intervals, results from Purdue et al. (1992), shown as Purdue, and from Huff and Angel (1992) shown as Huff are given in Figs. 1.1 and 1.2. These results show considerable variation.

In some cases the NOAA results are much lower – for example, for Indianapolis – than the results from Huff and from Purdue. In others, – for example for South Bend – the NOAA results are in between those by Huff and Purdue. In some cases the NOAA results partly agree with those by Huff. The main conclusion from these results is that it may be difficult to accept any of these results as definitive. Investigation of these variations is one of the objectives of the present study.

(c) Intensity-Duration-Frequency (IDF) Curves

IDF curves are commonly used to estimate the average design rainfall intensity for a given recurrence interval (T) over a range of durations (t). These curves are available for many cities. They may also be constructed by using the information available in rainfall atlases. IDF curves are commonly represented as in Eqs. 1.1 and 1.2

$$i = \frac{c}{t^e + f} \quad (1.1)$$

$$\text{or} \quad i = \frac{c}{(t + e)^f} \quad (1.2)$$

where c , e and f depend on locations (Wenzel, 1982).

A generalized i-d-f relationship was constructed by Chen (1983) using the 10-year, 1-hr. rainfall (R_1^{10}) , 10-year, 24-hr. rainfall R_{24}^{10} and the 100-year, 1-hr. rainfall (R_1^{100}) from TP-40. These depths are indicative of the variation in rainfall patterns in terms of depth ratio (R_1^T / R_{24}^T) for a recurrence interval T and the depth ratio (R_t^{100} / R_t^{10}) for duration t . The general relation given by Chen (1983) for rainfall depth R_t^T (in.) for any duration t (min.) and return period T (yrs.) is given in Eq. 1.3.

$$R_t^T = \frac{a_1 R_1^{10} [(x-1)\log(T/10)+1](t/60)}{(t+b_1)^{c_1}} \quad (1.3)$$

In eq. 1.3, $x = (R_1^{100} / R_1^{10})$ and T is the return period. a_1 , b_1 and c_1 are coefficients which are expressed as functions of (R_1^{10} / R_{24}^{10}) . The basic assumption in the derivation of eq. 1.3 is that the ratio (R_1^{10} / R_{24}^{10}) does not vary significantly with T . For T larger than 10, the return periods of annual maximum series are not significantly different from those obtained from partial duration series.

The assumption that the ratio R_1^{10} / R_{24}^{10} is constant was tested, to a limited extent, by using the information in the table presented below. This ratio is tabulated below for the NOAA and Purdue et al. (1992) results.

Ratio R_1^{10} / R_{24}^{10}		
	NOAA	Purdue et al. (1992)
Indianapolis	0.5	0.43
Evansville	0.44	0.45
Fort Wayne	0.5	0.45
South Bend	0.43	0.47

The variation in the ratio is much larger for different locations with NOAA results than for Purdue results. These results raise some questions about the robustness of NOAA results.

The similarity between Eqs. 1.2 and 1.3 is obvious. Although Chen (1983) developed Eq. 1.3 for use in the U.S., the concept is applicable for any region, although the coefficients must be estimated for the region under consideration.

(d) Temporal Distribution of Rainfall

The time distribution of precipitation or a hyetograph is needed in many design problems. This information is also essential in using rainfall-runoff models. In the design of drainage systems, the time of occurrence of the maximum intensity rainfall from the beginning of storms may be of significance.

Design storms may be developed from IDF curves. An alternative is the use of Huff (1967) curves. Huff (1967) curves are dimensionless hyetographs computed by using observed rainfall. Because they are estimated from observed data, they include, intrinsically, the temporal correlations between rainfall values. These correlations are important when short duration rainfall values are considered, as they frequently are, in drainage design. Although Huff curves can be generated for each station, if a single set of Huff curves can be developed for the entire state of Indiana, it would simplify matters considerably. Consequently, it is worthwhile examining whether a single set of Huff curves can be developed for Indiana.

In view of these considerations the objectives of the research discussed in this report are as follows.

The first objective is to acquire rainfall data for different time scales – such as hourly and daily – for stations in Indiana as well as in the neighboring states from the National Weather Service. These data are to be checked for accuracy and consistency. These issues are discussed in Chapter 2.

The second objective is to perform an intensity-duration-frequency analysis of the data. The results of this analysis are to be compared with the previous results to document changes. They are also compared to the results by the NOAA study and the Huff-Angel (1992) report. These results are presented in Chapter 3.

Relationships for Indiana, similar to those developed by Chen (1983), are developed for obtaining the intensity-duration relationship for any location in Indiana. The accuracy of the results of this study is established by using observed data. These results are presented in Chapter 4.

There are several sources of rainfall information available. These are compared and some assumptions behind them are tested. The results of the comparative analysis are presented in Chapter 5.

A set of Huff curves which may be used for the State of Indiana are generated. The results of Huff curve development are presented in Chapter 6.

The general conclusions are presented in Chapter 7.

II. Data Used in the Study

2.1. Data Sources and Study Area

Hourly precipitation data from 144 rainfall stations in Indiana are collected. These data are taken from the Hourly Precipitation Database (TD 3240) of National Climate Data Center (NCDC, <http://www.ncdc.noaa.gov/oa/ncdc.html>). Most of these data have been collected and recorded since July, 1948 until the present. The summary of number of stations in Indiana and the duration of data is shown in Table 2.1.1.

	TD3240
Years	Num. of Station
0-19	62
20-29	18
30-39	20
40-49	10
50-	34

Table 2.1.1 - Numbers of Stations in Different Recorded Period

2.2. Combination of Data from Nearby Stations

The length of observation period affects the result of frequency analysis. The longer the recorded length, the better are the results. If the recorded period is not long enough, it is not possible to properly fit the probability distributions. In order to perform an acceptable analysis, a minimum length of data is required. However, although there are 144 rainfall stations in Indiana, most of the recorded length of data is under twenty years and therefore not sufficient for frequency analysis.

Owing to this insufficiency, an assumption is made to increase the recorded length. Within a small distance, rainfall characteristics are similar, especially in a homogeneous

region such as Indiana. Hence, it is reasonable to combine data from nearby stations. In many of the cases, when a rainfall station is discontinued, we find that there is another new nearby station continuing the data collection. Therefore, although these two stations are not the same and have different identification numbers, their recorded data would be similar. In the present study, the maximum distance between two stations for combining the data is assumed to be 10 miles (16.09 km). A summary of number of stations versus their recorded length after the data are combined is given in Table 2.2.1. The complete list of all rainfall stations and the combinations are given in appendix A. Table 2.2.2 is an example of the information in appendix A. From these tables we can see that the recorded lengths of combined data are longer which would enable better fitting of distributions to them.

	TD3240 (After Combined)
Years	Num. of Station
0-19	26
20-29	5
30-39	12
40-49	1
50-	56

Table 2.2.1 - Numbers of Stations in Different Recorded Period after Data Combination

	COOPID	Combine to	STATION NAME	COUNTY	LAT	LON	ELEV	UTM_X	UTM_Y	Distance (km)	From	To	Total (Original)	Total (Combined)
1	120132		ALPINE 2 NE	Fayette	3934	-8510	259.1	657482.63	4381268.45		1949	2	2003	12
	124867	120132	LAUREL		3930	-8511	N/A	656200.26	4373839.92	7.54	1948	7	1948	10
2	120177		ANDERSON SEWAGE PLT	Madison	4006	-8543	257.6	609386.56	4439645.49		1974	8	2003	12
	120182	120177	ANDERSON WATERWORKS	Madison	4006	-8541	265.2	612227.85	4439687.02	2.84	1959	5	1959	5
	120172	120177	ANDERSON MOUNDS STAT	Madison	4005	-8537	262.1	617939.23	4437923.32	8.72	1948	7	1974	7
3	120200		ANGOLA	Steuben	4138	-8459	307.8	667975.03	4611031.33		1977	5	2003	12
	123134	120200	FREMONT	Steuben	4144	-8457	310.9	670487.32	4622199.93	11.45	1950	5	1976	12
	127243	120200	RAY POST OFFICE		4145	-8452	N/A	677372.16	4624218.97	16.19	1948	7	1950	4
4	120331		ATTICA 2 E	Fountain	4017	-8711	221.6	484415.59	4459221.34		1995	1	2003	12
	120328	120331	ATTICA	Fountain	4018	-8715	158.5	478753.75	4461085.13	5.96	1948	7	1994	12
5	120482		BATESVILLE WATERWORK	Ripley	3918	-8513	295.7	653772.70	4351584.77		1948	7	2003	12
6	120830		BLUFFTON 1 N	Wells	4045	-8510	251.5	654771.21	4512621.93		1971	7	2003	12
	120829	120830	BLUFFTON 1 N	Wells	4045	-8511	249.9	653364.13	4512592.67	1.41	1948	8	1971	6
	120824	120830	BLUFFTON	Wells	4047	-8510	263.7	654693.87	4516322.38	3.70	1948	7	1948	7

Table 2.2.2 - Example of TD3240 Hourly Precipitation Data

2.3. Station Selection Criterion

Those stations whose recorded data length is under twenty years, even after combining data from stations, are discarded. Data from 74 stations in Indiana are analyzed further. These stations are distributed all over Indiana. The location map of stations before and after stations are combined are shown in Figures 2.3.1 and 2.3.2.

For frequency analysis, it is necessary to calculate annual maximum precipitation for different durations. For this reason, the completeness of data during an entire year is important. Unfortunately, when data are checked, frequently there are periods when data are missing in a year. These periods exist for different reasons. For example, the breakdown of instruments, moving stations, or some other reasons will cause periods without data. Therefore, the length of an “acceptable” missing period must be decided. If the missing period is too long, data of the annual maximum event will be missed. On the contrary, if the missing period is too short, many observed records may have to be abandoned. In this study, a 3-month period is selected as the longest acceptable missing data period. Therefore stations with data length less than 9 months in a year are not considered further.

2.4. Computation of Annual Maximum Rainfall

After the data are organized as discussed earlier, they are used to calculate the annual maximum precipitation for different durations. These annual maximum values are used in frequency analysis. Durations of 1, 2, 3, 4, 6, 8, 12, 24, and 48 hours are used in this study. The annual maximum rainfall values are calculated for these durations.

Once again, often there is some incompleteness in the original data. Due to unspecified reasons, parts of the data are not recorded hourly. Instead, the total amount of

**Figure 2.3.1 - Rainfall Stations in Indiana
Before Data Combination**

**Figure 2.3.2 - Rainfall Stations in Indiana
After Data Combination**

precipitation for several hours is recorded. In some cases, these incomplete data are high rainfall events that should not be neglected. In the present study, these data are taken into account. In some cases, these incomplete data do contribute to the annual maximum value.

The annual maximum precipitation for 9 different durations in 74 stations mentioned in section 2.2 was estimated. An example of annual maximum data is shown in Table 2.4.1. Most of these maximum rainfall events happen in late spring, summer, and early fall.

The homogeneity of Indiana rainfall data was tested by using the homogeneity tests developed by Hosking and Wallis (1977). Of the three statistics, H_1 is considered as more important. If the statistics are less than 1, the data are considered to be homogeneous. The results of the homogeneity test for Indiana data are given in Table 2.4.2. According to these results the Indiana annual maximum rainfall are homogeneous.

Duration (hour)	Heterogeneity Measure		
	H_1	H_2	H_3
1	-0.12	-2.65	-2.92
2	0.17	-2.99	-3.09
3	-0.60	-2.17	-2.51
4	-0.83	-1.96	-2.47
6	-0.39	-1.09	-1.67
8	-0.15	-1.14	-1.62
12	0.30	-1.85	-2.10
24	0.21	-1.46	-2.12
48	-0.93	-2.11	-2.32

Table 2.4.2 - Homogeneity Test of Annual Maximum Precipitation Data

These results are computed by Ms. En-ching Hsu

year	Duration = 1 hour			Duration = 2 hour			Duration = 3 hour			Duration = 4 hour			Duration = 6 hour			Duration = 8 hour			Duration = 12 hour			Duration = 24 hour			Duration = 48 hour							
	M	D	T	Rain	M	D	T	Rain	M	D	T	Rain	M	D	T	Rain	M	D	T	Rain	M	D	T	Rain	M	D	T	Rain				
1972	4	13	23	0.95	4	13	23	1.40	4	13	23	2.25	4	13	23	2.38	4	13	23	2.42	4	13	23	3.00	4	13	17	3.45	4	13	19	3.94
1973	7	14	14	0.90	7	14	13	1.36	4	23	7	1.45	7	14	13	1.60	4	23	7	1.85	4	23	6	2.27	4	23	2	2.60	4	23	3	2.76
1974	4	1	19	0.83	4	1	19	1.03	3	6	2	1.37	5	29	24	1.52	3	6	2	1.59	3	6	1	1.60	3	6	1	1.60	5	29	15	2.50
1975	8	5	23	1.18	8	5	23	1.35	8	5	23	1.39	3	28	19	1.52	3	28	19	2.29	3	28	19	2.44	3	28	13	2.71	3	28	3	3.62
1976	7	28	24	1.30	7	28	24	1.45	7	28	24	1.55	7	28	24	1.65	7	28	24	1.65	7	28	24	1.80	2	17	16	2.10	2	16	24	3.29
1977	8	16	21	1.10	8	24	1	1.86	8	24	1	2.50	8	23	24	2.63	8	23	24	2.66	8	23	24	2.67	4	22	2	3.16	4	21	11	3.34
1978	12	3	7	1.05	12	3	6	1.36	12	3	6	1.56	12	3	4	1.72	12	3	6	2.12	12	3	4	2.48	12	3	3	3.61	12	3	3	3.66
1979	7	25	19	0.75	7	25	18	1.30	7	25	18	1.33	7	25	18	1.48	9	21	3	1.89	9	21	1	2.07	7	25	18	2.49	9	21	1	4.47
1980	6	28	22	1.17	7	22	9	1.46	7	22	9	1.77	6	28	22	2.14	6	28	21	2.15	6	28	22	2.21	6	28	21	2.94	6	28	21	2.94
1981	7	14	19	1.67	7	14	19	2.67	7	14	19	2.88	7	14	18	2.89	7	14	15	3.51	7	14	15	3.72	7	14	15	4.15	8	5	23	4.70
1982	8	16	3	1.02	8	16	3	1.77	8	16	2	2.03	8	16	2	2.28	8	16	1	2.66	8	15	24	2.67	8	15	22	2.68	1	22	6	3.61
1983	4	30	2	1.28	4	30	2	1.94	4	30	2	2.18	4	30	2	2.58	4	30	2	3.91	4	30	1	4.48	4	29	9	5.27	4	28	14	6.36
1984	7	4	7	0.75	5	7	15	1.25	5	7	15	1.54	5	7	15	1.54	11	1	16	1.80	11	1	16	1.80	11	1	11	2.00	5	6	2	3.28
1985	6	11	18	0.80	6	11	17	1.10	6	11	17	1.30	6	11	17	1.50	6	11	17	1.70	6	11	17	1.70	10	20	1	1.80	6	10	1	2.90
1986	7	31	8	1.20	7	31	8	2.10	7	31	7	2.30	7	31	7	2.40	7	31	7	2.40	7	31	7	2.60	2	1	22	3.00	2	1	22	3.70
1987	7	30	14	1.70	7	30	14	1.80	7	30	14	1.80	7	30	14	1.80	7	30	14	1.80	7	30	14	1.80	12	25	10	1.90	12	24	7	3.50
1988	7	18	11	1.30	7	19	2	1.60	7	19	1	1.90	7	19	1	1.90	1	19	12	2.30	1	19	11	2.40	1	19	6	2.90	7	18	10	4.10
1989	9	1	13	1.20	5	19	21	1.70	5	19	20	1.90	5	19	20	2.00	5	19	20	2.00	5	19	20	2.10	2	13	2	3.70	2	13	5	4.60
1990	5	15	14	1.00	5	15	13	1.10	5	28	10	1.40	5	28	9	1.60	2	15	8	2.20	2	15	8	2.50	2	15	4	4.10	2	15	4	4.10
1991	6	21	12	1.10	6	21	12	1.20	6	21	12	1.30	6	21	12	1.30	6	21	12	1.30	6	21	12	1.60	12	2	4	2.20	11	30	24	2.80
1992	6	23	21	1.00	6	23	21	1.10	7	20	21	1.20	7	23	23	1.40	7	23	23	1.60	7	23	23	1.70	7	23	3	2.20	3	17	20	2.40
1993	6	14	19	2.30	6	14	19	2.30	6	14	17	2.40	6	9	8	2.60	6	9	8	2.60	6	9	8	2.70	6	9	8	2.90	6	9	8	2.90
1994	8	29	1	1.00	8	28	24	1.10	6	26	6	1.20	6	26	5	1.30	10	18	24	1.80	10	18	24	1.90	10	18	19	1.90	4	29	20	2.40
1995	7	22	16	1.60	7	22	16	1.60	7	22	16	1.60	5	17	4	1.70	5	17	4	2.00	8	5	9	2.10	8	5	7	2.30	5	17	4	3.70
1996	12	23	21	1.00	12	23	21	1.40	12	23	20	1.50	4	20	1	1.60	12	23	17	1.70	6	8	23	1.80	3	19	5	2.10	6	8	23	3.50
1997	3	2	3	1.10	3	2	2	2.00	3	2	3	2.50	3	2	2	3.40	3	2	1	4.00	3	1	24	4.30	3	1	7	7.70	3	1	4	9.00
1998	6	22	21	1.40	6	22	20	1.90	6	22	19	2.20	6	22	19	2.50	6	22	19	2.50	6	22	19	2.50	6	22	19	2.50	6	21	1	3.20
1999	5	23	16	0.80	5	6	8	1.20	1	22	4	1.30	4	26	5	1.60	5	6	4	2.10	10	9	6	2.60	10	9	3	3.10	1	22	3	4.00
2000	8	27	3	1.10	4	7	21	1.20	1	2	21	1.30	8	27	3	1.50	1	2	20	1.60	12	16	2	1.90	1	2	20	2.90	1	2	20	2.90
2001	9	8	9	1.10	9	8	9	1.20	6	19	11	1.70	6	19	11	2.00	6	19	9	2.60	6	19	7	2.70	6	19	7	2.70	11	27	18	3.50
2002	9	26	24	1.40	9	26	24	2.30	9	26	23	2.90	9	26	22	3.20	9	26	22	4.10	9	26	20	4.60	9	26	16	5.20	9	26	9	5.60
2003	9	3	18	1.10	9	3	17	1.50	9	3	16	1.90	9	3	15	2.00	9	3	16	2.50	9	3	15	2.60	9	3	15	2.60	9	2	6	4.90

Table 2.4.1 - Example of Annual Maximum Precipitation (in inches) for Different Durations. M, D, T are the Month, Day and Time of the Event

Chapter III. Frequency Analysis of Data

3.1. Return Period, Probability Density and Plotting Positions

The definition of the return period T is that a given rainfall depth x with a return period T is exceeded, on the average, once in T years. Hence, the cumulative probability of non-exceedence, $F(X_T)$ is given by:

$$F(X_T) = P(X_T \leq x) = 1 - P(X_T > x) = 1 - \frac{1}{T} \quad (3.1.1)$$

For observed data, an estimated probability based on its order is estimated. The assigned probability of non-exceedence is $F = (F(X_T))$, which may be based on the “plotting position”. The plotting-position formula used in this study is the Gringorton formula given in Eq. 3.1.2,

$$P(X_T > x) = \frac{m - 0.44}{N + 0.12} \quad (3.1.2)$$

where N is the number of years, m is the rank in descending order.

Different probability density functions may be fitted to the observed rainfall data. The adequacy of the fitted distributions is tested by using the goodness-of-fit tests. Five probability distributions are tested in this study for the Indiana data. These are Extreme Value Type I distribution, Generalized Extreme Value distribution, Pearson Type III distribution, Log-Pearson Type III distribution, and Pareto distribution. Some details about these distributions are given below.

Extreme Value Type I & Generalized Extreme Value Distributions

Extreme Value Type I distribution (EV(1)) and Generalized Extreme Value distribution (GEV) are similar distributions. EV(1) distribution is a special case of GEV distribution.

The probability density function $f(x)$ of EV(1) distribution is:

$$f(x) = \frac{1}{\alpha} \exp \left[- \left(\frac{x - \beta}{\alpha} \right) - e^{-\left(\frac{x - \beta}{\alpha} \right)} \right], \quad -\infty < x < \infty \quad (3.1.3)$$

The cumulative probability function $F(x)$ of EV(1) distribution is:

$$F(x) = \exp \left[- e^{-\left(\frac{x - \beta}{\alpha} \right)} \right] \quad (3.1.4)$$

The probability density function $f(x)$ for GEV distribution is:

$$f(x) = \frac{1}{\alpha} \left[1 - k \left(\frac{x - u}{\alpha} \right) \right]^{1/k - 1} e^{-\left[1 - k \left(\frac{x - u}{\alpha} \right) \right]^{1/k}},$$

$$\text{when } k < 0, u + \alpha/k < x < \infty \quad k > 0, -\infty < x < u + \alpha/k \quad (3.1.5)$$

The cumulative probability function $F(x)$ of GEV distribution is:

$$F(x) = \exp \left\{ - \left[1 - k \left(\frac{x - u}{\alpha} \right) \right]^{1/k} \right\} \quad (3.1.6)$$

When $k \rightarrow 0$ in GEV distribution, equation (3.1.5) and (3.1.6) become (3.1.3) and (3.1.4). Thus EV(1) distribution is the special case of GEV distribution.

The method of moments is used in this study for parameter estimation. The basic statistics of annual maximum precipitation data are used to estimate the parameters. An example of the statistics is shown in Table 3.1.1.

For EV(1) distribution the relationship between the moments and parameters are given below.

$$\hat{\alpha} = \frac{\sqrt{6}}{\pi} \sqrt{m_2} \quad (3.1.7)$$

$$\hat{\beta} = m'_1 - 0.45005 \sqrt{m_2} \quad (3.1.8)$$

COOPID	120132					
Duration (hour)	Annual Maximum x			Log10 x		
	Average (in)	Standard Deviation (in)	Skewness Coefficient	Average (in)	Standard Deviation (in)	Skewness Coefficient
1	1.1989	0.4274	1.4463	0.0555	0.1396	0.5573
2	1.6287	0.5753	0.8178	0.1864	0.1494	0.1401
3	1.8131	0.6439	0.8475	0.2327	0.1504	0.0930
4	1.9056	0.6900	1.1075	0.2544	0.1489	0.2379
6	2.1022	0.7133	1.3946	0.3011	0.1355	0.3993
8	2.2576	0.7159	1.2433	0.3342	0.1298	0.2224
12	2.4473	0.7191	1.0243	0.3713	0.1238	0.0006
24	2.7744	0.8616	1.1472	0.4243	0.1276	0.2522
48	3.1976	1.0614	1.6116	0.4845	0.1308	0.4888

Table 3.1.1. Example of the Basic Statistics of the Annual Maximum Precipitation

m'_1 is the mean (the first moment) of the annual maximum precipitation, and m_2 is the variance (the second central moment) of the distribution.

For GEV distribution the relationships are,

$$C_s = m_3 / m_2^{3/2} = \frac{\hat{k} \left(-\Gamma(1+3\hat{k}) + 3\Gamma(1+\hat{k})\Gamma(1+2\hat{k}) - 2\Gamma^3(1+\hat{k}) \right)}{|\hat{k}| \left[\Gamma(1+2\hat{k}) - \Gamma^2(1+\hat{k}) \right]^{3/2}} \quad (3.1.9)$$

$$\hat{\alpha} = \left[m_2 \hat{k}^2 / \left\{ \Gamma(1+2\hat{k}) - \Gamma^2(1+\hat{k}) \right\} \right]^{1/2} \quad (3.1.10)$$

$$\hat{u} = m'_1 + \frac{\hat{\alpha}}{\hat{k}} \left[1 - \Gamma(1+\hat{k}) \right] \quad (3.1.11)$$

m_3 is the third central moment of the annual maximum precipitation, C_s is the coefficient of skewness, and $\Gamma(x)$ is the gamma function, where:

$$\Gamma(x) = \int_0^\infty t^{x-1} e^{-t} dt \quad (3.1.12)$$

Eq. 3.1.9 is solved numerically for $\hat{k}$. From Rao and Hamed (2000) the

approximate relationships for $\hat{k}$ and C_s are given as follows:

a. EV2 (2): $\hat{k} < 0$ ($1.14 < C_s < 10$), $R^2 = 1$,

$$\begin{aligned} \hat{k} = & 0.2858221 - 0.357983C_s + 0.116659C_s^2 - 0.022725C_s^3 \\ & + 0.002604C_s^4 - 0.000161C_s^5 + 0.000004C_s^6 \end{aligned} \quad (3.1.13)$$

b. EV3 (3): $\hat{k} > 0$ ($-2 < C_s < 1.14$), $R^2 = 1$,

$$\begin{aligned} \hat{k} = & 0.277648 - 0.322016C_s + 0.060278C_s^2 + 0.016759C_s^3 \\ & - 0.005873C_s^4 - 0.00244C_s^5 - 0.000050C_s^6 \end{aligned} \quad (3.1.14)$$

b. EV2 (3): $\hat{k} < 0$ ($-10 < C_s < 0$), $R^2 = 0.999978$,

$$\begin{aligned} \hat{k} = & -0.50405 - 0.00861C_s + 0.015497C_s^2 + 0.005613C_s^3 \\ & + 0.00087C_s^4 + 0.000065C_s^5 \end{aligned} \quad (3.1.15)$$

When $-2 < C_s < 0$, $\hat{k}$ may have two possible answers. Both solutions are used to estimate the parameters. The distributions are compared to determine the one which best fits the data.

The T-year return period quantile estimates $\hat{x}_T$ and the frequency factors K_T are obtained from the following equations. These are derived from eq. 3.1.16

$$\hat{x}_T = m'_1 + K_T \sqrt{m_2} \quad (3.1.16)$$

For EV(1):

$$\hat{x}_T = \hat{\beta} - \hat{\alpha} \ln[-\ln(1 - 1/T)] \quad (3.1.17)$$

$$K_T = \frac{\sqrt{6}}{\pi} \{-0.5772157 - \ln[-\ln(1 - 1/T)]\} \quad (3.1.18)$$

For GEV:

$$\hat{x}_T = \hat{u} + \frac{\hat{\alpha}}{\hat{k}} \left\{ 1 - [-\ln(1 - 1/T)]^{\hat{k}} \right\} \quad (3.1.19)$$

$$K_T = \frac{\hat{k}\Gamma(1+\hat{k}) - [-\ln(1-1/T)]^{\hat{k}}}{\left|\hat{k}\left[\Gamma(1+2\hat{k}) - \Gamma^2(1+\hat{k})\right]^{1/2}\right|} \quad (3.1.20)$$

Table 3.1.2 is an example of the parameters for the data in table 3.1.1. The estimates of rainfall depth for different return periods are estimated by using these parameters. Rainfall depth estimates for different durations obtained by using EV(1) and GEV distributions are given in table 3.1.3.

COOPID	120132	EV(1)					GEV					
Duration	N	EV(1)- β	EV(1)- α	χ^2	χ^2 -Test	KS-Test	GEV-u	GEV- α	GEV-k	χ^2	χ^2 -Test	KS-Test
1	55	1.0066	0.3333	4.95	O	O	1.0037	0.3124	-0.0462	6.22	O	O
2	55	1.3698	0.4485	1.89	O	O	1.3776	0.4822	0.0603	2.91	O	O
3	55	1.5233	0.5020	2.91	O	O	1.5310	0.5361	0.0541	4.18	O	O
4	55	1.5951	0.5380	9.27	X	O	1.5957	0.5413	0.0047	9.27	X	O
6	55	1.7812	0.5561	5.96	O	O	1.7769	0.5268	-0.0391	4.95	O	O
8	55	1.9355	0.5582	4.44	O	O	1.9334	0.5457	-0.0168	4.44	O	O
12	55	2.1236	0.5607	8.00	X	O	2.1264	0.5750	0.0198	8.26	X	O
24	55	2.3866	0.6718	1.13	O	O	2.3864	0.6705	-0.0014	1.64	O	O
48	55	2.7200	0.8276	0.36	O	O	2.7108	0.7510	-0.0674	1.38	O	O

N: Record length

Table 3.1.2 - Example of the Estimated Parameters and Goodness-of-fit Results for EV(1) & GEV Distribution

COOPID	120132	EV(1)				GEV				
DUR	2 year	5 year	10 year	50 year	100 year	2 year	5 year	10 year	50 year	100 year
1	1.13	1.51	1.76	2.31	2.54	1.12	1.49	1.74	2.34	2.61
2	1.53	2.04	2.38	3.12	3.43	1.55	2.07	2.39	3.05	3.32
3	1.71	2.28	2.65	3.48	3.83	1.73	2.30	2.67	3.42	3.71
4	1.79	2.40	2.81	3.69	4.07	1.79	2.40	2.81	3.69	4.06
6	1.99	2.62	3.03	3.95	4.34	1.97	2.59	3.02	4.00	4.43
8	2.14	2.77	3.19	4.11	4.50	2.13	2.76	3.19	4.13	4.54
12	2.33	2.96	3.39	4.31	4.70	2.34	2.98	3.39	4.29	4.65
24	2.63	3.39	3.90	5.01	5.48	2.63	3.39	3.90	5.01	5.48
48	3.02	3.96	4.58	5.95	6.53	2.99	3.90	4.54	6.06	6.76

Table 3.1.3 - Example of the Rainfall Estimates from EV(1) & GEV

Pearson Type III & Log-Pearson Type III Distributions Statistics

The Pearson Type III (P(3)) and Log-Pearson Type III distributions (LP(3)) are fitted to the data. P(3) and LP(3) are commonly used in hydrologic frequency analysis. The

estimation equations for P(3) distribution are given below.

For P(3), the probability density function $f(x)$ is:

$$f(x) = \frac{1}{\alpha\Gamma(\beta)} \left(\frac{x-\gamma}{\alpha} \right)^{\beta-1} e^{-\left(\frac{x-\gamma}{\alpha}\right)}, \quad \gamma < x < \infty \quad (3.1.21)$$

The cumulative probability function $F(x)$ is:

$$F(x) = \frac{1}{\alpha\Gamma(\beta)} \int_{\gamma}^x \left(\frac{x-\gamma}{\alpha} \right)^{\beta-1} e^{-\left(\frac{x-\gamma}{\alpha}\right)} dx \quad (3.1.22)$$

The equations to estimate the parameters of P(3) distribution are as follows:

$$\hat{\beta} = (2 / C_s)^2 \quad (3.1.23)$$

$$\hat{\alpha} = \sqrt{(m_2 / \hat{\beta})} \quad (3.1.24)$$

$$\hat{\gamma} = m'_1 - \sqrt{m_2 \hat{\beta}} \quad (3.1.25)$$

To estimate K_T and x_T in eq. 3.1.16, the following equation is used.

$$K_T = z + (z^2 - 1)k + \frac{1}{3}(z^3 - 6z)k^2 - (z^2 - 1)k^3 + zk^4 + \frac{1}{3}k^5 \quad (3.1.26)$$

$$x_T = \hat{\alpha}\hat{\beta} + \hat{\gamma} + K_T \sqrt{\hat{\alpha}^2 \hat{\beta}} \quad (3.1.27)$$

Where z is the standard normal variate corresponding to a probability of non-exceedence of $F = 1 - 1/T$, and $k = C_s / 6$. An example of the estimated

COOPID	120132	P(3)						LP(3)					
Duration	N	P(3)- γ	P(3)- α	P(3)- β	χ^2	χ^2 -Test	KS-Test	LP(3)- γ	LP(3)- α	LP(3)- β	χ^2	χ^2 -Test	KS-Test
1	55	6.08E-01	3.09E-01	1.91E+00	6.74	X	O	-4.46E-01	3.89E-02	1.29E+01	4.94	O	O
2	55	2.22E-01	2.35E-01	5.98E+00	4.18	O	O	-1.95E+00	1.05E-02	2.04E+02	1.64	O	O
3	55	2.94E-01	2.73E-01	5.57E+00	4.18	O	O	-3.00E+00	6.99E-03	4.63E+02	2.66	O	O
4	55	6.60E-01	3.82E-01	3.26E+00	8.51	X	O	-9.97E-01	1.77E-02	7.07E+01	6.98	X	O
6	55	1.08E+00	4.97E-01	2.06E+00	5.45	O	O	-3.78E-01	2.71E-02	2.51E+01	4.43	O	O
8	55	1.11E+00	4.45E-01	2.59E+00	5.71	O	O	-8.33E-01	1.44E-02	8.09E+01	4.44	O	O
12	55	1.04E+00	3.68E-01	3.81E+00	8.25	X	O	-3.88E+02	3.95E-05	9.82E+06	10.22	X	O
24	55	1.27E+00	4.94E-01	3.04E+00	3.16	O	O	-5.88E-01	1.61E-02	6.29E+01	1.62	O	O
48	55	1.88E+00	8.55E-01	1.54E+00	2.40	O	O	-5.09E-02	3.20E-02	1.67E+01	1.38	O	O

N: Record length

Table 3.1.4. Example of the Estimated Parameters and Goodness-of-fit Results for P(3) & LP(3) Distribution

parameters of P(3) and LP(3) is given in Table 3.1.4. An example of estimates of rainfall depth for different return periods is given in Table 3.1.5.

COOPID	120132	P(3)				LP(3)				
DUR	2 year	5 year	10 year	50 year	100 year	2 year	5 year	10 year	50 year	100 year
1	1.10	1.49	1.76	2.36	2.61	1.10	1.47	1.74	2.41	2.73
2	1.55	2.07	2.40	3.05	3.30	1.52	2.05	2.40	3.19	3.54
3	1.72	2.31	2.67	3.41	3.70	1.70	2.28	2.67	3.54	3.92
4	1.78	2.42	2.83	3.69	4.04	1.77	2.39	2.81	3.79	4.23
6	1.95	2.60	3.05	4.03	4.44	1.96	2.58	3.02	4.05	4.53
8	2.12	2.77	3.21	4.15	4.54	2.13	2.77	3.19	4.13	4.54
12	2.33	2.99	3.41	4.28	4.64	2.35	2.99	3.39	4.22	4.56
24	2.62	3.41	3.92	5.02	5.47	2.62	3.39	3.90	5.05	5.56
48	2.93	3.91	4.59	6.15	6.81	2.98	3.89	4.54	6.11	6.84

Table 3.1.5 - Example of the Rainfall Estimates of P(3) & LP(3)

Pareto Distribution

The probability density function $f(x)$ of the Pareto distribution is:

$$f(x) = \frac{1}{\alpha} \left[1 - \frac{k}{\alpha} (x - \varepsilon) \right]^{1/k-1}, \quad k \leq 0, \varepsilon \leq x < \infty$$

$$k > 0, \varepsilon \leq x < \varepsilon + \alpha/k \quad (3.1.28)$$

The cumulative probability function $F(x)$ is:

$$F(x) = 1 - \left[1 - \frac{k}{\alpha} (x - \varepsilon) \right]^{1/k} \quad (3.1.29)$$

The method of moments parameter estimates for Pareto distribution are given in Eqs. 3.1.30 – 3.1.32.

$$C_s = \frac{2(1 - \hat{k})(1 + 2\hat{k})^{1/2}}{(1 + 3\hat{k})} \quad (3.1.30)$$

$$\hat{\alpha} = \left[m_2 (1 + \hat{k})^2 (1 + 2\hat{k}) \right]^{1/2} \quad (3.1.31)$$

$$\hat{\varepsilon} = m'_1 - \hat{\alpha} / (1 + \hat{k}) \quad (3.1.32)$$

$\hat{k}$ in eq. 3.1.30 is estimated numerically. Newton-Raphson iterative procedure is used to solve for $\hat{k}$. The initial value of $\hat{k}$ may be taken as zero for positive skew and -1/2 for negative skew. The equations used for estimation of k are given below.

$$k_{n+1} = k_n - F(k_n) / F'(k_n) \quad (3.1.33)$$

$$F(k) = 2(1-k)(1+2k)^{1/2} / (1+3k) - C_s \quad (3.1.34)$$

$$F'(k) = \frac{-2(1+2k)^{1/2}}{(1+3k)} + \frac{2(1-k)(1+2k)^{-1/2}}{(1+3k)} - \frac{6(1-k)(1+2k)^{1/2}}{(1+3k)^2} \quad (3.1.35)$$

For Pareto distribution, the data should be greater than the lower bound $\hat{\varepsilon}$. Therefore after $\hat{\varepsilon}$ is obtained, one should check if the lowest observed value is greater than $\hat{\varepsilon}$. If $\hat{\varepsilon}$ is greater than the lowest observed value, the smallest data value should be removed and the parameter is estimated again. This procedure is repeated until all the data used for parameter estimation are greater than the lower bound $\hat{\varepsilon}$.

However, a problem arises with the Pareto distribution. In this study, in order to satisfy the above restriction, for some stations, up to 30% of the data had to be removed to make the observed data are greater than $\hat{\varepsilon}$. In doing so, though we may have a good fit, the resulting estimates may be unrealistic. To solve this problem in Pareto distribution, Hogg and Tanis (1988), provided modified moment estimates by considering the smallest observation x_1 . Hogg and Tanis' distribution has the following probability density function given in eq. 3.1.31,

$$f(x_1) = \frac{1}{\alpha/N} \left[1 - \frac{(k/N)}{(\alpha/N)} (x - \varepsilon) \right]^{\left(\frac{1}{k/N} \right) - 1} \quad (3.1.36)$$

where N is data length. The equations used to estimate $\hat{\varepsilon}$ are:

$$\hat{\varepsilon} = -b + \sqrt{b^2 - C} \quad (3.1.37)$$

$$b = (N - 1) \frac{m_2}{(m'_1 - x_1)} - m'_1 \quad (3.1.38)$$

$$C = (m'_1)^2 - m_2 + 2m_2 \frac{(m_1 - Nx_1)}{(m_1 - x_1)} \quad (3.1.39)$$

For $\hat{k}$ and $\hat{\alpha}$:

$$\hat{k} = \frac{1}{2} \left[(m'_1 - \varepsilon)^2 / m_2 - 1 \right] \quad (3.1.40)$$

$$\hat{\alpha} = (m'_1 - \varepsilon) (1 + \hat{k}) \quad (3.1.41)$$

Both the original and modified method were used in this study. The results were computed and compared.

To estimate K_T and x_T , the following equations are used

$$K_T = \frac{(1 + 2\hat{k})^{1/2}}{\hat{k}} \left[(1 + \hat{k}) (1 - T^{-\hat{k}}) - \hat{k} \right] \quad (3.1.42)$$

$$\hat{x}_T = \hat{\varepsilon} + \frac{\hat{\alpha}}{\hat{k}} \left[1 - T^{-\hat{k}} \right] \quad (3.1.43)$$

An example of the estimates of parameters of data are given in Table 3.1.6. The quantile estimates for different return periods are given in Table 3.1.7.

COOPID	120132		Pareto							Pareto (modified)					
Duration	N1	N2	Pareto- ϵ	Pareto- α	Pareto-k	χ^2	χ^2 -Test	KS-Test	Pareto- ϵ	Pareto- α	Pareto-k	χ^2	χ^2 -Test	KS-Test	
1	55	50	7.96E-01	4.94E-01	9.20E-02	4.04	O	O	5.83E-01	9.48E-01	5.38E-01	9.27	X	O	
2	55	52	9.62E-01	9.43E-01	3.22E-01	3.19	O	O	7.75E-01	1.37E+00	6.00E-01	5.96	O	O	
3	55	46	1.24E+00	9.19E-01	2.62E-01	1.48	O	O	8.20E-01	1.68E+00	6.90E-01	6.98	O	O	
4	55	49	1.26E+00	8.79E-01	1.66E-01	2.57	O	O	8.48E-01	1.77E+00	6.74E-01	9.53	X	O	
6	55	46	1.54E+00	7.69E-01	6.89E-02	4.61	O	O	9.53E-01	2.07E+00	7.98E-01	14.62	X	O	
8	55	46	1.70E+00	7.85E-01	8.78E-02	4.09	O	O	9.38E-01	2.90E+00	1.20E+00	25.31	X	X	
12	55	39	2.03E+00	8.01E-01	1.24E-01	1.77	O	O	9.15E-01	4.24E+00	1.77E+00	34.98	X	X	
24	55	40	2.27E+00	9.12E-01	8.99E-02	3.80	O	O	1.39E+00	2.50E+00	8.00E-01	12.84	X	O	
48	55	30	2.97E+00	8.77E-01	-4.42E-02	0.00	O	O	1.74E+00	2.10E+00	4.40E-01	4.44	O	O	

N1: Number of total recorded years, N2: Number of years greater than ε

Table 3.1.6 – Example of the Estimated Parameters and Goodness-of-fit Results for Pareto Distribution

COOPID	120132	Pareto				Pareto (modified)				
DUR	2 year	5 year	10 year	50 year	100 year	2 year	5 year	10 year	50 year	100 year
1	1.13	1.54	1.82	2.42	2.65	1.13	1.60	1.83	2.13	2.20
2	1.55	2.15	2.50	3.06	3.23	1.55	2.18	2.48	2.83	2.91
3	1.82	2.44	2.83	3.49	3.70	1.74	2.45	2.76	3.09	3.15
4	1.83	2.50	2.94	3.79	4.09	1.83	2.59	2.92	3.29	3.36
6	2.06	2.71	3.18	4.17	4.57	2.05	2.83	3.13	3.43	3.48
8	2.23	2.88	3.33	4.30	4.67	2.30	3.01	3.21	3.34	3.35
12	2.56	3.20	3.63	4.51	4.84	2.61	3.17	3.27	3.31	3.31
24	2.88	3.64	4.17	5.28	5.71	2.72	3.65	4.02	4.37	4.43
48	3.59	4.43	5.10	6.72	7.45	2.99	4.16	4.78	5.65	5.88

Table 3.1.7 – Example of the Rainfall Estimates of Pareto Distribution

3.2. Goodness-of-Fit of the Distributions

After estimating the parameters, the goodness-of-fit of distribution are evaluated.

Two common tests are used to estimate the goodness-of-fit.

3.2.1. Chi-Square Test

In the chi-square (χ^2) test, data are first divided into k class intervals. In this study, we choose $k \approx \sqrt{n}$, where n is the number of the total recorded years. However, the average number of values in any group should be larger than 5. Hence, χ^2 -test was not carried out when the number of observations is less than 25. The χ^2 -value is calculated by:

$$\chi^2_{sample} = \sum_{j=1}^k \frac{(O_j - E_j)^2}{E_j} \quad (3.2.1)$$

O_j is the observed number of events in the class interval j , and E_j is the number of events that would be expected from the theoretical distribution. The significance level α is selected to be 10% to find $\chi^2_{\nu, 1-\alpha}$, where ν is the degree of freedom, and m is the number of parameters estimated.

$$\nu = k - 1 - m \quad (3.2.2)$$

If $\chi^2_{sample} < \chi^2_{\nu, 1-\alpha}$, then the distribution is accepted. Otherwise, the distribution is rejected.

3.2.2. Kolmogorov-Smirnov Test

In Kolmogorov-Smirnov (KS) test, the test statistic D is defined by:

$$D = \max_{i=1}^n |F^*(x_i) - F(x_i)| \quad (3.2.3)$$

$F^*(x_i)$ is the estimate of the cumulative probability of the i -th observation from the Gringorton formula (eq. 3.1.2). $F(x_i)$ is the cumulative probability of the i -th data from the probability distribution. In other words, D is the maximum absolute deviation between the observed and fitted distribution. The value of D must be less than a tabulated value of $D_{critical}$ at the required confidence level (Kolmogorov (1933); also Hogg and Tanis (1988) (Table VIII) for the Pareto distribution to be used. Typical results of the goodness-of-fit tests are shown in Tables 3.1.2, 3.1.4 and 3.1.6.

3.2.3. Dimensionless Plots of Cumulative Distribution

Another way to examine the goodness of fit is to plot them as dimensionless figures. If a distribution is suitable for one rainfall station, the plotting result for different durations should be similar and parallel to each other, as shown in Figure 3.2.1. Based on the results in Figure 3.2.1, the most significant variable is the mean value for different durations. Dividing depth by its corresponding mean depth, the results are dimensionless, as shown in Figure 3.2.2. It can be observed that if a distribution is suitable for different durations, the dimensionless result will be more linear. Thus dimensionless plots can provide a quick visual check on the adequacy of a distribution.

Dimensional Plot of Station 120132 (GEV result)

Figure 3.2.1 –Plots for Different Durations

Dimensionless Plot of Station 120132 (GEV result)

Figure 3.2.2 – Dimensionless Plots for Different Durations

In order to check if a single distribution can be applied for all the data, dimensionless plots of different distribution are plotted. That is, results from all stations in Indiana are plotted together. The correlation r^2 coefficient of these plots can guide in the selection of the distribution. Higher r^2 means that the rainfall is homogeneous in the entire state and the distribution used is acceptable; lower r^2 means that the distribution is not suitable. An example of these results is in figure 3.2.3.

Figure 3.2.3 - Example of the Generalized GEV Fitting Result

3.2.3. Summary of Results

The summary of all χ^2 and KS test is given in Table 3.2.8. Examples of plots are shown in figures 3.2.4 – 3.2.9.

	EV(1)		GEV		P(3)	
	χ^2	KS	χ^2	KS	χ^2	KS
total cases	639	666	639	666	639	666
not pass	165	9	200	4	240	25
(%)	25.82	1.35	31.30	0.60	37.56	3.75

	LP(3)		Pareto		Pareto (modified)	
	χ^2	KS	χ^2	KS	χ^2	KS
total cases	639	666	569	666	621	666
not pass	191	4	124	6	430	152
(%)	29.89	0.60	21.79	0.90	69.24	22.82

Table 3.2.8 – The Summary of the χ^2 Test and the KS Test

EV(1), GEV, P(3), and LP(3) distributions provide good fits for most of the stations. For these four distributions, from the result of the χ^2 test, EV(1) passes most tests, then LP(3) and GEV, while the fit of P(3) distribution is not as good. The dimensionless plots of these results are also good unless there are extremely high values in the data. EV(1) has the best result. However, GEV & P(3) can fit better for higher extreme values. It is surprising that LP(3), which is traditionally considered the best model in hydrological frequency analysis, does not perform as the best distribution. Besides that, LP(3) also does not provide a good fit for extremely high values.

For Pareto distribution, though the original method can provide good results, we are forced to remove about 15% of the smaller observed data, and the resulting fit becomes unrealistic. Applying the modified parameter estimation method of Pareto distribution we can keep all the data for analysis, but the results are not as good. From this point of view, Pareto distribution is not suitable for the Indiana rainfall data.

From the KS test, except for the modified Pareto method, all other distributions pass the test. The few cases which do not pass the KS test are affected by their extremely high

COOPID 120132 IN

Figure 3.2.4 - Example of the EV(1) Plots

COOPID 120132 IN

Figure 3.2.5 - Example of the GEV Plots

COOPID 120132 IN

Figure 3.2.6 - Example of the P(3) Plots

COOPID 120132 IN

Figure 3.2.7 - Example of the LP(3) Plots

Figure 3.2.8 - Example of the Pareto Plots

Figure 3.2.9 - Example of the Pareto Plots

values. If we treat those values as outliers and remove them, the result will pass the KS test and the fit will become better. However, this modification may not reflect the reality. Therefore we will keep the outliers in the data.

From the dimensionless graphs, we can notice that r^2 values are high except for the Pareto distribution. It reveals that rainfall in Indiana may be considered to be homogeneous. We can also observe that GEV and P(3) are better in predicting high values. Considering all factors, GEV is selected for further analysis.

IV. Intensity-Duration-Frequency (IDF) Relationships for Indiana

4.1. Introduction

Quite often, while performing hydrologic design, for any particular location, the rainfall depth for specified duration and return period are needed. Though such information can be found in tables and figures in some publications, such as Rainfall Frequency Atlas of the U.S. Weather Bureau (TP-40), it may not be accurate because they were developed a long time ago or are based on questionable assumptions. Also, this information may be limited to specific durations and return periods. These may have to be interpolated to get the information for a specific duration and location. Therefore, it is desired to develop methods to obtain intensity-duration-frequency for any location in Indiana. Such relationships are developed in this chapter.

The rainfall intensity is defined as,

$$i = \frac{P}{t} \quad (4.1.1)$$

where i is the rainfall intensity (inch/hour), P is the rainfall depth (inch), t is the rainfall duration (hour). The IDF equation for a specified return period and location is in the following form:

$$i = \frac{a}{(60t + b)^c} \quad (4.1.2)$$

a , b , c are dimensional IDF coefficients. These coefficients would be different for different rainfall durations and locations. Using the IDF equation, users can easily get the rainfall intensity or depth for a desired duration by specifying the duration t . However, it has some drawbacks. First, for different return periods, different IDF coefficients must be used. Consequently the intensity for a specific return period is obtained by interpolation. Secondly, equations such as Eq. 4.1.2, are not available for all locations.

Usually, IDF information is provided only for larger cities.

To overcome these disadvantages of the IDF method, Chen (1983) proposed a generalized intensity-duration-frequency relationship based on the data in TP-40. Before Chen's method is introduced, several variables are defined.

i_t^T : Rainfall intensity (inch/hour) for duration t (hour) and return period T (year)

P_t^T : Rainfall depth (inch) for duration t (hour) and return period T (year),

$$i_t^T = \frac{P_t^T}{t} \quad (4.1.3)$$

R_T : Ratio of 1-hour, T -year rainfall depth to 24-hour, T -year rainfall depth in percentage, which is:

$$R_T = \frac{P_1^T}{P_{24}^T} \times 100 \quad (4.1.4)$$

x_t : Ratio of 100-year, t -hour rainfall depth to 10-year, t -hour rainfall depth, which is:

$$x_t = \frac{P_t^{100}}{P_t^{10}} \quad (4.1.5)$$

Examples of calculation of R_T and x_t are shown below:

Example 4.1.1. Calculation of Ratio R_T and x_t

For a station, the GEV rainfall depth is given. R_T and x_t are to be evaluated.

Such as:

$$R_{10} = P_1^{10} / P_{24}^{10} = 1.745 / 3.898 = 44.76 \quad (\%)$$

$$R_{100} = P_1^{100} / P_{24}^{100} = 2.605 / 5.481 = 47.53 \quad (\%)$$

$$x_1 = P_1^{100} / P_1^{10} = 2.605 / 1.745 = 1.493$$

$$x_{24} = P_{24}^{100} / P_{24}^{10} = 5.481 / 3.898 = 1.406$$

Detailed information for this station is given in Table 4.1.1.

Duration t (hour)	Return period T (year)						$x_t =$ P_t^{100} / P_t^{10}
	2	5	10	25	50	100	
1	1.119	1.489	1.745	2.081	2.340	2.605	1.493
2	1.552	2.069	2.393	2.781	3.054	3.315	1.386
3	1.726	2.303	2.667	3.105	3.417	3.714	1.393
4	1.794	2.405	2.807	3.314	3.688	4.059	1.446
6	1.971	2.591	3.016	3.572	3.998	4.432	1.469
8	2.134	2.762	3.185	3.727	4.134	4.544	1.427
12	2.336	2.976	3.392	3.909	4.286	4.655	1.372
18	2.507	3.225	3.704	4.314	4.770	5.225	1.411
24	2.632	3.393	3.898	4.536	5.010	5.481	1.406
$R_T (\%) =$ $(P_1^T / P_{24}^T) * 100$	42.52	43.88	44.76	45.87	46.70	47.53	

Table 4.1.1 – Illustration of R_T Calculation

Ratios R_{10} and x_1 are used in Chen's method. Chen's equations are shown as follows:

$$i_t^T = \frac{a'}{(60t + b_1)^{c_1}} \quad (4.1.6)$$

$$a' = a_1 i_1^{10} \log(10^{(2-x_1)} T^{(x_1-1)}) \quad (4.1.7)$$

$$a_1 = a_1(R_{10}) \quad (4.1.8)$$

$$b_1 = b_1(R_{10}) \quad (4.1.9)$$

$$c_1 = c_1(R_{10}) \quad (4.1.10)$$

where a_1 , b_1 , c_1 are Chen's coefficients, which are functions of R_{10} , as shown in Figure 4.1.1. Eq. 4.1.6 is a form of generalized IDF formula. The biggest advantage of Chen's method is that it can be used to compute IDF functions if the 10-year 1-hour

Figure 4.1.1 - Chen's Coefficients a_1 , b_1 , c_1 as a Function of R_{10}

rainfall (P_1^{10}), the 10-year 24-hour rainfall (P_{24}^{10}), and the 100-year 1-hour rainfall (P_1^{100}) are known. Using these three known rainfall depths, ratio $R_{10} = P_1^{10}/P_{24}^{10}$ and $x_1 = P_1^{100}/P_1^{10}$ are calculated. Using these, rainfall intensity and depth for other return periods and durations can be computed. This method is easy to use and has been shown to be valid for different locations. The detailed procedure is given below with an example:

1. 10-year, 1-hour rainfall depth P_1^{10} , 10-year, 24-hour rainfall depth P_{24}^{10} , and 100-year, 1-hour rainfall depth P_1^{100} are used to evaluate R_{10} and x_1 using Eq. 4.1.4 and Eq. 4.1.5:
2. R_{10} in percentage is used to estimate the value of a_1 , b_1 , and c_1 from Figure 4.1.1.
3. The intensity i_1^{10} is same as P_1^{10} because the duration is 1 hour.
4. a' is calculated by using Eq. 4.1.7.
5. The desired T -year, t -hour rainfall intensity i_t^T (inch/hour) is computed by using Eq. 4.1.6.

Example 4.1.2. Chen's Method

For the data in Table 4.1.1, GEV rainfall $P_1^{10} = 1.745$ inch, $P_{24}^{10} = 3.898$ inch, and $P_1^{100} = 2.605$ inch are known. P_3^5 and P_2^{25} are to be calculated by Chen's method.

1. $R_{10} = P_1^{10}/P_{24}^{10} = 1.745/3.898 = 44.76$ (%)
 $x_1 = P_1^{100}/P_1^{10} = 2.605/1.745 = 1.493$
2. From Figure 4.1.1, when $R_{10} = 44.76$ (%)
 $a_1(R_{10}) = 26.8$

$$b_1(R_{10}) = 8.8$$

$$c_1(R_{10}) = 0.783$$

$$3. \quad i_1^{10} = \frac{P_1^{10}}{1} = 1.745 \text{ inch/hour}$$

$$4. \quad \text{For } P_3^5:$$

$$a' = a_1 i_1^{10} \log(10^{(2-x_1)} T^{(x_1-1)}) = 26.8 * 1.745 * \log(10^{(2-1.493)} 5^{(1.493-1)}) = 39.83$$

$$i_3^5 = \frac{39.83}{(60 * 3 + 8.8)^{0.783}} = 0.658 \text{ inch/hour}$$

$$P_3^5 = i_3^5 * 3 = 0.658 * 3 = 1.97 \text{ inch}$$

$$\text{For } P_2^{25}:$$

$$a' = a_1 i_1^{10} \log(10^{(2-x_1)} T^{(x_1-1)}) = 26.8 * 1.745 * \log(10^{(2-1.493)} 25^{(1.493-1)}) = 55.94$$

$$i_2^{25} = \frac{55.94}{(60 * 2 + 8.8)^{0.783}} = 1.246 \text{ inch/hour}$$

Figure 4.1.2 - GEV Rainfall vs. Chen's Estimate

$$P_2^{25} = i_2^{25} * 2 = 1.246 * 2 = 2.49 \text{ inch}$$

5. The 2-hour and 3-hour Chen's estimate and GEV rainfall are plotted together in figure 4.1.2. In this case, Chen's method underestimates the GEV rainfall intensity for this station.

Chen used the IDF formula and assumed that the IDF coefficients b and c are functions of ratio R_{10} , and the IDF coefficient a is the function of ratio R_{10} , x_1 , and P_1^{10} . Chen's method is based on two assumptions:

- (1) The ratio $R_T = P_1^T / P_{24}^T$ used in the determination of a_1 , b_1 , and c_1 values at a location does not vary significantly with T . Thus, R_{10} can be used to represent R_T for all different return periods.
- (2) The ratio $x_t = P_t^{100} / P_t^{10}$ used in the determination of a' values at a location does not vary significantly with t . Thus, x_1 can be used to represent x_t for different durations.

These assumptions are tested by using the generalized extreme value distribution (GEV) rainfall estimates for Indiana.

4.2. Intensity - Duration Relationship

Chen's method can be divided into two parts: intensity-duration relationship and intensity-return period relationship. The intensity-duration relationship is discussed below.

The intensity-duration relationship provides the transformation from known 1-hour rainfall intensity to unknown t -hour rainfall intensity. It is in the generalized IDF form:

$$i_t^T = \frac{a_1 i_1^T}{(60t + b_1)^{c_1}} \quad (4.2.1)$$

$$a_1 = a_1(R_T) \quad (4.2.2)$$

$$b_1 = b_1(R_T) \quad (4.2.3)$$

$$c_1 = c_1(R_T) \quad (4.2.4)$$

Parameters a_1 , b_1 , c_1 are functions of the ratios of rainfall depths of duration T , R_T . Hence, for different return periods, these coefficients could be different because R_T might be different. Chen assumed that R_T does not change significantly with T and used R_{10} to represent R_T to simplify this relationship.

The intensity-return period relationship provides the transformation from known 10-year rainfall intensity to unknown T -year rainfall intensity:

$$i_t^T = i_1^{10} \log(10^{(2-x_t)} T^{(x_t-1)}) \quad (4.2.5)$$

Again, x_t could be different for different durations. Chen assumed that x_t does not change significantly with t and used x_1 to represent all x_t .

Assume $t = 1$ hr into Eq. 4.2.5 and multiply it by a_1 to get Eq. 4.2.6.

$$a' = a_1 i_1^T = a_1 i_1^{10} \log(10^{(2-x_1)} T^{(x_1-1)}) \quad (4.2.6)$$

Combining Eq. 4.2.6 and Eq. 4.2.1, substituting R_T by R_{10} , we get Chen's model (Eq. 4.1.6).

In this section, the intensity-duration relationship is discussed. The parameters a_1 , b_1 , c_1 are re-estimated by using the GEV estimates of rainfall for Indiana. The validity of simplifications made by Chen is also tested. The intensity-return period relationship is discussed in section 4.3.

4.2.1. Intensity - Duration Relationship for Indiana

The most crucial aspect of the intensity-duration relationship is the behavior of coefficients a_1 , b_1 , and c_1 . These three coefficients determine the precision of the estimated rainfall intensity and depth. As explained before, Chen assumed these three coefficients are functions of R_{10} , and provided the relationship in figure 4.1.1. This relationship was constructed in 1976 by using TP-40 precipitation data of the entire United States. The TP-40 atlas was constructed by using even earlier data in 1960's. Hence, checking the precision of these relationships is of interest.

To check the accuracy of Chen's relationship for Indiana data, figure 4.1.1 is used with the TP-40 ratios R_T . For every rainfall station, the TP-40 rainfall depth is looked up and used to calculate $R_T = P_1^T / P_{24}^T$. R_T values are used to find out the corresponding a_1 , b_1 , c_1 from Figure 4.1.1. This is Chen's original setup. Hence, the obtained coefficients a_1 , b_1 , c_1 can be regarded as the IDF coefficients for the corresponding rainfall stations. These values are substituted into Eq. 4.2.1 to obtain estimated rainfall intensities, as shown in the example below:

Example 4.2.1. Intensity - Duration Relationship

For station 120132 in Indiana, the intensity-duration relationship is used to calculate rainfall intensities other than 1-hour and 24-hour. Take $T = 5$ year for example:

1. $R_5 = P_1^5 / P_{24}^5 = 1.72 / 3.66 = 46.99 \text{ (\%)}$

2. From fig. 4.1.1, when $R_5 = 46.99 \text{ (\%)}$

$$a_1(R_5) = 28.6$$

$$b_1(R_5) = 9.28$$

$$c_1(R_5) = 0.796$$

$$3. \quad i_1^5 = \frac{P_1^5}{1} = 1.72 \text{ inch/hour}$$

4. Other intensities are calculated by Eq. 4.2.1, such as:

$$i_2^5 = \frac{1.72 * 28.6}{(60 * 2 + 9.28)^{0.796}} = 1.022 \text{ inch/hour}$$

$$i_{18}^5 = \frac{1.72 * 28.6}{(60 * 18 + 9.28)^{0.796}} = 0.187 \text{ inch/hour}$$

$$5. \quad P_2^5 = i_2^5 * 2 = 1.022 * 2 = 2.044 \text{ inch}$$

$$P_{18}^5 = i_{18}^5 * 18 = 3.366 \text{ inch}$$

Detailed information is shown in Table 4.2.1.

	Return period T (year)					
	2	5	10	25	50	100
P_1^T (inch)	1.35	1.72	1.95	2.25	2.50	2.77
P_{24}^T (inch)	2.95	3.66	4.16	4.75	5.24	5.69
R_T (%)	45.76	46.99	46.88	47.37	47.71	48.68
i_1^T (inch/hour)	1.35	1.72	1.95	2.25	2.50	2.77
a_1	27.5	28.6	28.5	28.9	29.2	30.0
b_1	8.98	9.28	9.25	9.37	9.45	9.66
c_1	0.788	0.796	0.796	0.799	0.801	0.808
i_2^T (inch/hour)	0.806	1.022	1.159	1.335	1.480	1.631
i_3^T (inch/hour)	0.597	0.754	0.856	0.984	1.091	1.199
i_4^T (inch/hour)	0.480	0.606	0.688	0.790	0.875	0.960
i_6^T (inch/hour)	0.352	0.443	0.503	0.577	0.639	0.699
i_8^T (inch/hour)	0.282	0.354	0.402	0.461	0.510	0.557
i_{12}^T (inch/hour)	0.206	0.258	0.293	0.335	0.370	0.404
i_{18}^T (inch/hour)	0.150	0.187	0.213	0.243	0.268	0.292

Table 4.2.1 - Applying the Intensity - Duration Relationship to Station 120132

After intensities are estimated, the estimated depth can be obtained by multiplying

the rainfall duration. The estimation error ε and the percentage estimation error ξ are defined in Eq. 4.2.7 and 4.2.8:

$$\varepsilon = (\text{Depth for this station from GEV}) - (\text{estimated depth}) \quad (4.2.7)$$

$$\xi = \{[(\text{GEV depth}) - (\text{estimated depth})] / (\text{estimated depth})\} * 100 \quad (4.2.8)$$

The estimation error ε indicates the difference between the GEV rainfall depth and the rainfall depth estimated by Chen's method. If the estimation is good, the error ε and ξ should be close to zero. To evaluate the performance of the estimates, three statistics are also computed: the standard deviation of the estimation error ε , the average of the absolute percentage estimation error $|\xi|$, and the coefficient of determination r^2 . The reason to adopt $|\xi|$ is that now we are evaluating rainfall depth under different return periods and durations. Therefore, scales are different. Adopting the absolute percentage difference provides us a dimensionless statistic for the evaluation. The result for this station is shown in Table 4.2.2. The error is about 9%.

Standard Deviation of Estimation Error ε (inch)	0.437
Average Absolute Percentage Error $ \xi $ (%)	8.672
Coefficient of Determination r^2	0.8854

Table 4.2.2 - Statistics of Evaluation of Chen's Intensity - Duration Relationship

Next, the estimated rainfall depths are plotted against the corresponding estimates from GEV distribution of every station in Indiana, as shown in Figure 4.2.1. If this relationship is good, the calculated intensities should be close to the GEV values. The

relationship between these should be linear.

Figure 4.2.1 - Test of Rainfall - Duration Relationship of the Indiana Data

The result shows that the standard deviation of the error is about 0.437 inch. The absolute percentage difference is 8.672%, the r^2 value for this test is 0.8622, and an obvious trend is seen from Figure 4.2.1. All these results indicate that Chen's intensity-duration formula offers a good estimate. However, as mentioned above, Figure 4.1.1 which provides the relationship between R_T and Chen's coefficients a_1 , b_1 , c_1 is built on TP-40 which was developed by using rainfall data from the entire US. The estimate may be improved by using more recent and local rainfall data in Indiana. In the following analysis, we will re-evaluate the coefficients a_1 , b_1 , and c_1 by using the Indiana data, which may give better rainfall depth estimates.

4.2.2. Evaluation of Chen's Coefficients for Indiana Rainfall Data

In Eq. 4.2.1, divide by i_1^T on both sides and take logarithms to get Eq 4.2.9:

$$\log(i_t^T / i_1^T) - \log a_1 + c_1 \log(60t + b_1) = 0 \quad (4.2.9)$$

where, $a_1 = a_1(R_T)$, $b_1 = b_1(R_T)$, $c_1 = c_1(R_T)$ are functions of R_T . $R_T = P_1^T / P_{24}^T$ may be different for different return periods and stations. If the data fit perfectly into this relationship, the left side of Eq. 4.2.9 should equal to zero. For the real data, though this relationship is nearly impossible to be equal to zero, it should be close to zero if these parameters are valid. Thus, the following function F is minimized to obtain a_1 , b_1 , c_1 for a given return period T of a certain station:

$$F(a_1(R_T), b_1(R_T), c_1(R_T)) = \sum_{t=1}^{24} [\log(i_t^T / i_1^T) - \log a_1(R_T) + c_1(R_T) \log(60t + b_1(R_T))]^2 \quad (4.2.10)$$

Example 4.2.2. Estimating Coefficients of Chen's Method

For station 120132, GEV intensities are given. For every return period T , Eq. 4.2.10 is minimized by changing coefficients a_1 , b_1 , c_1 . Take $T = 5$ year & 25 year for instances:

For $T = 5$ years, for $R_5 = 43.88$ (%)

$$\begin{aligned} & \min F(a_1(R_5), b_1(R_5), c_1(R_5)) \\ &= \min \sum_{t=1}^{24} [\log(i_t^5 / i_1^5) - \log a_1(R_5) + c_1(R_5) \log(60t + b_1(R_5))]^2 = 1.04 * 10^{-3} \end{aligned}$$

Hence, when $R_5 = 43.88$ (%),

$$a_1 = 49.7, \quad b_1 = 31.21, \quad c_1 = 0.860$$

Compared to the Chen's original coefficient, when $R_{10} = 43.88$:

$$a_1 = 25.9, \quad b_1 = 8.51, \quad c_1 = 0.772$$

For $T = 25$ years, for $R_{25} = 45.87$ (%)

$$\min F(a_1(R_{25}), b_1(R_{25}), c_1(R_{25}))$$

$$= \min \sum_{t=1}^{24} \left[\log(i_t^{25} / i_1^{25}) - \log a_1(R_{25}) + c_1(R_{25}) \log(60t + b_1(R_{25})) \right]^2 = 1.02 * 10^{-3}$$

Hence, when $R_{25} = 45.87$ (%),

$$a_1 = 52.5, \quad b_1 = 30.71, \quad c_1 = 0.874$$

Compared to the Chen's original coefficient, when $R_{25} = 45.87$:

$$a_1 = 27.6, \quad b_1 = 9.01, \quad c_1 = 0.789$$

The results for other return periods are shown in Table 4.2.3. In both the cases, the re-estimated coefficients are quite different with Chen's original coefficients. To make sure these solutions are accurate, the re-estimated coefficients are used to calculate rainfall intensities by Chen's method, and the results are plotted in Figure 4.2.2.

	Return period T (year)					
	2	5	10	25	50	100
R_T (%)	42.52	43.88	44.76	45.87	46.70	47.53
$\min F$	9.37E-04	1.04E-03	9.83E-04	1.02E-03	1.30E-03	1.89E-03
a_1	44.7	49.7	51.4	52.5	52.7	52.7
b_1	30.51	31.21	31.13	30.71	30.24	29.69
c_1	0.839	0.860	0.868	0.874	0.878	0.880

Table 4.2.3 - Calculation of Coefficients of Station 120132

The full line is the estimate by new coefficients, and the dashed line gives the rainfall by original coefficients. It is clear that the new coefficients offer better estimates, and they are quite different with Chen's original coefficients.

The numerical method used in this study is the quasi-Newton method. Return

Figure 4.2.2 – Results by Re-estimated Coefficients

periods T of 2, 5, 10, 25, 50, and 100 year are selected. This calculation is performed for every return period and data from every station in Indiana. The coefficients a_1 , b_1 , and c_1 are separately computed for different stations and return periods. The relationship between new coefficients and R_T is plotted in Figure 4.2.3 for all the cases. It is seen that there is a trend in c_1 , but not an obvious trend in a_1 , even worse in b_1 .

These parameters and i_1^T of GEV rainfall are used to compute the rainfall intensities for all the stations. Again, the estimation errors are computed, and the statistics of estimation error are shown in Table 4.2.4. These estimates versus the GEV value are plotted for the Indiana data. The result is shown in Figure 4.2.4.

Standard Deviation of Estimation Error ε (inch)	0.090
Average Absolute Percentage Error $ \xi $ (%)	1.468
Coefficient of Determination r^2	0.9948

Table 4.2.4 - Statistics of Estimates with Coefficient Estimated
for Every Station and Return Period

Figure 4.2.3 - Chen's Parameters Estimated by Different Stations and Return Periods

Figure 4.2.4 – GEV vs. New Result by Parameters Estimated for Every Station and Return Period

The standard deviation of estimation error is 0.09 inch, and the average absolute percentage difference is only 1.468%. This relationship follows a straight line, and the r^2 is nearly 1, which means that the estimates are very close to GEV values. This result is reasonable because for every return period and every station, the parameters are obtained separately. Consequently, for every single R_T value, a best set of coefficients is obtained. However, these can not be used in practice in this form because parameters a_1 , b_1 , c_1 do not have a simple relationship with R_T . Also, due to the scattered distribution in Figure 4.2.3, it may be difficult to get a good relationship between R_T and a_1 , b_1 , and c_1 .

Thus, to obtain a simple relationship for coefficients a_1 , b_1 , c_1 and R_T , an

assumption should be made. We may assume that in a small interval of R_T , the coefficients a_1 , b_1 , and c_1 are constant. Hence, we can reclassify all rainfall data by the value of R_T , in an increasing order. Then, the data are divided into small groups. For each group, R_T can be represented by the average $\bar{R}$ because the values of R_T are in a relatively small range and do not change much. Also, there should be one best value of coefficients for each group. Hence, a grouping method was developed. Detailed procedure is explained below.

For every station, treat the GEV rainfall intensities as sets of data by R_T values. Such as, for station 120132,

$$R_2 = 42.52 \text{ (\%)}, i_1^2 = 1.119 \text{ in/hr}, i_2^2 = 0.776 \text{ in/hr}, \dots, i_{24}^2 = 0.110 \text{ in/hr} \quad \text{-data 1 (} T = 2\text{yr)}$$

$$R_5 = 43.88 \text{ (\%)}, i_1^5 = 1.489 \text{ in/hr}, i_2^5 = 1.035 \text{ in/hr}, \dots, i_{24}^5 = 0.141 \text{ in/hr} \quad \text{-data 2 (} T = 5\text{yr)}$$

$$R_{10} = 44.76 \text{ (\%)}, i_1^{10}, i_2^{10}, \dots, i_{24}^{10} \quad \text{-data 3 (} T = 10\text{yr)}$$

$$R_{25} = 45.87 \text{ (\%)}, i_1^{25}, i_2^{25}, \dots, i_{24}^{25} \quad \text{-data 4 (} T = 25\text{yr)}$$

$$R_{50} = 46.70 \text{ (\%)}, i_1^{50}, i_2^{50}, \dots, i_{24}^{50} \quad \text{-data 5 (} T = 50\text{yr)}$$

$$R_{100} = 47.53 \text{ (\%)}, i_1^{100}, i_2^{100}, \dots, i_{24}^{100} \quad \text{-data 6 (} T = 100\text{yr)}$$

Hence, for a constant return period T , just treat these as six sets of data as vectors, it becomes $\{R_j, i_{1j}, i_{2j}, \dots, i_{24j}\}_j$, $j = 1, \dots, 6$. For k stations, we have

$\{R_{jk}, i_{1jk}, i_{2jk}, \dots, i_{24jk}\}_{jk}$ sets of data.

Rank all these data vectors by the value of R_j in an increasing order. They become

$\{R'_j, i_{1j}, i_{2j}, \dots, i_{24j}\}_j$, $j = 1, \dots, 6 * k$. Note that R'_j is used to denote R_j after reordering them in an increasing order. For each vector, there should be a corresponding best solution of coefficients a_1 , b_1 , and c_1 . From our assumption, we know that for vectors with close R'_j value, the corresponding coefficients should also be close to each other. Hence, grouping data into small groups by R'_j value, and obtaining the representative coefficients for each group is the next phase.

Coefficients	$R_T (\%) = P_1^T / P_{24}^T$					
	10	15	20	30	40	60
a_1	4.58	6.57	8.91	14.35	22.57	40.01
b_1	-2.84	-0.80	1.04	4.12	7.48	11.52
c_1	0.309	0.420	0.507	0.632	0.738	0.872

Table 4.2.5 - Grouped Coefficients used by Chen (1976)

The question of appropriate grouping interval should be considered. In Chen's original paper, data set with R_T near 10%, 15%, 20%, 30%, 40%, and 60% was grouped together, and the corresponding coefficients were obtained for these six groups, shown in Table 4.2.5. Then these values were used to plot Figure 4.1.1.

It is possible to have different results by using different grouping criteria. In this study, several grouping choices are selected and tested:

- Group by 8 equal data number groups. For each group, numbers of data vectors are the same.
- Group by 10 equal data number groups. For each group, numbers of data vectors are the same.

c. Group by equal R_T spacing. For example, for data with R_T from 25%-30% are in the 1st group, data with R_T from 30%-35% are in the 2nd group ... etc. The interval chosen in this study is 5%.

After group is assigned, for group m , there are p data vectors: $\{R'_j, i_{1j}, i_{2j}, \dots, i_{24j}\}_j$,

$j = 1, \dots, p$. Take the average $\bar{R}_m$ of all R'_j as the representative R value in group m .

Coefficients can be estimated by minimizing Equation 4.2.11:

$$F(a_{1m}, b_{1m}, c_{1m}) = \sum_{j=1}^p \sum_{t=1}^{24} [\log(i_{tj}/i_{1j}) - \log a_{1m} + c_{1m} \log(60t + b_{1m})]^2 \quad (4.2.11)$$

a_{1m} , b_{1m} , c_{1m} are denoted as the coefficient which minimize the rainfall data in the m -th group. $\bar{R}_m$ values are plotted versus a_{1m} , b_{1m} , c_{1m} to identify if any trend exists.

An example is shown below:

Example 4.2.3. Obtaining Parameters by Grouped Data

Parameters are estimated by using the Indiana Data of 74 rainfall stations. All data sets are ranked by R and divided into 10 intervals by the increasing R order. Brief calculation is shown below:

All GEV rainfall intensity data sets in Indiana:

$$\{R_j, i_{1j}, i_{2j}, \dots, i_{24j}\}_j, \quad j = 1, \dots, 6 * 74$$

Reorder the data by R_j in an increasing order, it becomes:

$$\{R'_j, i_{1j}, i_{2j}, \dots, i_{24j}\}_j, \quad j = 1, \dots, 6 * 74$$

For group 1 ($m = 1$), there are $6 * 74 / 10 \approx 44$ ($p = 44$) sets of data in this group:

$$\{R_j, i_{1j}, i_{2j}, \dots, i_{24j}\}_j, \quad j = 1, \dots, 44$$

Minimize Eq. 4.2.9 to estimate a_{11} , b_{11} , c_{11} :

$$\min F(a_{11}, b_{11}, c_{11}) = \min \sum_{j=1}^{44} \sum_{t=1}^{24} [\log(i_{t,j}/i_{1,j}) - \log a_{11} + c_{11} \log(60t + b_{11})]^2$$

The result for group 1:

$$a_{11} = 32.2$$

$$b_{11} = 34.96$$

$$c_{11} = 0.762$$

$$\bar{R}_1 = 33.47$$

The results for other groups are shown in Table 4.2.6:

$R_{\text{avg.}}$	a_1	b_1	c_1
33.47	32.2	34.96	0.762
37.37	42.4	40.21	0.814
38.99	36.6	28.58	0.801
40.50	36.1	25.11	0.804
41.64	34.9	22.99	0.803
42.61	38.2	25.07	0.818
43.66	35.8	20.89	0.813
44.79	34.9	18.23	0.813
46.45	38.1	19.96	0.830
50.87	61.9	35.00	0.907

Table 4.2.6 – Estimation of Parameters by Grouped Data

Besides applying this analysis for data from all the stations in Indiana, stations with record greater than 50 years are selected, and this procedure is repeated again. The result is shown in Figure 4.2.5. From these figures, it can be seen that though the results change from different grouping ways, we can observe that a second order trend exists. So the 2nd order polynomial is fitted to those coefficients with $\bar{R}$. These fitted coefficients are

Figure 4.2.5 - Revised Coefficient Estimates with Grouped Data
8 Equal Data Number Groups

R	a ₁	b ₁	c ₁
34.08	32.43	33.65	0.7653
38.03	38.51	34.22	0.8036
39.96	37.30	27.39	0.8068
41.51	37.00	25.46	0.8109
42.73	34.86	20.88	0.8068
44.09	36.72	21.69	0.8176
45.79	37.42	19.88	0.8257
50.14	57.44	32.62	0.8951

Figure 4.2.5 - Revised Coefficient Estimates with Grouped Data (contd.)
10 Equal Data Number Groups

R	a ₁	b ₁	c ₁
33.47	32.19	34.96	0.7616
37.37	42.41	40.21	0.8142
38.99	36.62	28.58	0.8009
40.50	36.07	25.11	0.8042
41.64	34.89	22.99	0.8032
42.61	38.16	25.07	0.8184
43.66	35.76	20.89	0.8131
44.79	34.89	18.23	0.8133
46.45	38.14	19.96	0.8302
50.87	61.86	35.00	0.9069

Figure 4.2.5 - Revised Coefficient Estimates with Grouped Data (contd.)
Equal Spacing Groups

R	a_1	b_1	c_1
26.95	36.97	61.66	0.7521
33.01	36.81	42.84	0.7777
37.96	36.37	30.82	0.7961
42.59	36.41	23.08	0.8120
46.84	40.33	21.83	0.8387
51.99	79.25	43.77	0.9436
56.69	47.44	18.17	0.8867
61.73	76.41	32.76	0.9622

Figure 4.2.5 - Revised Coefficient Estimates with Grouped Data (contd.)
Group with Stations with Records Greater Than 50 Years
in 8 Equal Data Number Groups

R	a ₁	b ₁	c ₁
36.62	46.12	46.75	0.8215
39.01	40.70	33.60	0.8147
40.64	37.50	26.56	0.8099
41.79	36.83	24.67	0.8114
42.84	39.20	25.55	0.8229
44.13	37.07	21.14	0.8198
45.64	42.03	24.70	0.8415
49.21	59.09	33.50	0.8975

Figure 4.2.5 - Revised Coefficient Estimates with Grouped Data (contd.)
Group with Stations with Records Greater Than 50 Years
in 10 Equal Data Number Groups

R	a ₁	b ₁	c ₁
36.30	40.65	41.28	0.8033
38.47	44.86	40.10	0.8254
39.89	40.57	31.45	0.8176
40.98	35.51	23.93	0.8039
41.92	39.17	26.74	0.8202
42.72	39.23	25.74	0.8226
43.75	39.76	24.61	0.8280
44.72	36.01	19.27	0.8175
46.25	43.51	25.17	0.8485
49.82	64.63	36.57	0.9111

Figure 4.2.5 - Revised Coefficient Estimates with Grouped Data (contd.)
 Group with Stations with Records Greater Than 50 Years
 in Equal Spacing Groups

R	a ₁	b ₁	c ₁
34.03	68.47	70.82	0.8667
38.10	41.58	37.37	0.8137
42.53	38.34	24.97	0.8190
46.70	43.26	24.31	0.8486
51.97	101.14	52.04	0.9775

used to re-estimate rainfall intensities. These estimated intensities are plotted against GEV intensities as Figure 4.2.6, and the statistics of estimation error are shown in Table 4.2.7.

Estiamted by	All Stations			Stations with records ≥ 50 years		
Grouping Method	8 groups	10 groups	every 5%	8 groups	10 groups	every 5%
Stdev of ε (inch)	0.234	0.235	0.207	0.507	0.494	0.502
Average of $ \xi $ (%)	3.657	3.769	4.334	8.420	8.234	9.515
r^2	0.9643	0.9640	0.9721	0.8334	0.8416	0.8370

Table 4.2.7 – Results of Coefficients Estimated
by using Different Groupings

From these figures, it can be observed that by applying different grouping methods, the coefficients will be different, but the results are not good. The r^2 value is not high for some cases, the standard deviation of error is high, and the estimates are not close to those from GEV distribution. Different grouping methods affect the estimation very much, and it is also hard to decide which grouping method is the best one. Consequently, a better method should be developed to determine the relationships between the coefficients and R_T .

Another method was developed to estimate these coefficients related to R_T . That is, from the results shown above, the three coefficients a_1 , b_1 , c_1 are assumed to be 2nd order functions of R_T as shown in Eq. 4.2.12 – 4.2.14,

$$a_1(R_T) = A_2 R_T^2 + A_1 R_T + A_0 \quad (4.2.12)$$

$$b_1(R_T) = B_2 R_T^2 + B_1 R_T + B_0 \quad (4.2.13)$$

GEV vs. Revised Estimate (Coefficients Estimated by All Stations
in 8 Equal Number Groups)

GEV vs. Revised Estimate (Coefficients Estimated by All Stations
in 10 Equal Number Groups)

Figure 4.2.6 – Rainfall Estimates by Using Revised Coefficients

GEV vs. Revised Estimate (Coefficients Estimated by All Stations in Euqal Spacing)

GEV vs. Revised Estimate (Coefficients Estimated by Stations With Records Greater Than 50 Years in 8 Euqal Number Groups)

Figure 4.2.6 – Rainfall Estimates by Using Revised Coefficients (contd.)

GEV vs. Revised Estimate (Coefficients Estimated by Stations With Records
Greater Than 50 Years in 10 Euqal Number Groups)

GEV vs. Revised Estimate (Coefficients Estimated by Stations With Records
Greater Than 50 Years in Euqal Spacing)

Figure 4.2.6 – Rainfall Estimates by Using Revised Coefficients (contd.)

$$c_1(R_T) = C_2 R_T^2 + C_1 R_T + C_0 \quad (4.2.14)$$

where, $A_2, A_1, A_0, B_2, B_1, B_0, C_2, C_1$, and C_0 are the unknown coefficients. Function F in Eq. 4.2.11 is minimized to estimate these coefficients numerically with the entire GEV intensity data set without grouping. Those coefficients obtained from previous grouping methods are used as good initial guesses. The result is shown in Table 4.2.8. These coefficients are used to recompute intensities, compared with the GEV results. The statistics of estimation error are shown in Table 4.2.9. These rainfall estimates versus GEV values are plotted in Figure 4.2.7.

A_0	A_1	A_2
1.3082E+02	-4.4805E+00	5.3849E-02
B_0	B_1	B_2
2.6592E+02	-9.6719E+00	9.4128E-02
C_0	C_1	C_2
8.8668E-01	-6.7227E-03	1.1946E-04

Table 4.2.8 - The 2nd Order Coefficients to Estimate a_1, b_1 , and c_1

Standard Deviation of Estimation Error ε (inch)	0.195
Average Absolute Percentage Error $ \xi $ (%)	3.075
Coefficient of Determination r^2	0.9756

Table 4.2.9 - Statistics of Estimates with Coefficients
Estimated by 2nd Order Polynomials of R_T

The advantage of assuming coefficients as second order functions of R_T directly is that there is no grouping necessary, and the solution satisfies the overall minimization function. Disadvantage is that the difficulty in numerical calculation increases. However, with a good initial guess, the best solution is found. Comparing the results in Table 4.2.9

Figure 4.2.7 – GEV vs. Revised Estimates by Assuming Parameters as 2nd Order Functions of R

to those in Table 4.2.2, and Figs. 4.2.7 and 4.2.1, the standard deviation of error decreases from 0.437 inch to 0.195 inch, the average absolute percentage difference decreases from 8.672% to 3.075%, and r^2 improves from 0.8622 to 0.9756, and the relationship appears more linear. Consequently, these coefficients are better.

These results were tested with data from individual stations. Four stations, Indianapolis (124259), Evansville (122738), Fort Wayne (123037), and West Lafayette (129430) were selected for this test. The rainfall computed with Chen's original coefficients and revised coefficients are plotted against the rainfall from GEV values, are shown in Figure 4.2.8. The statistics of estimation error are shown in Table 4.2.10. The results indicate that the modified coefficients work as well or better than Chen's original coefficients.

Figure 4.2.8 – Rainfall Estimates by Original and Modified Coefficients

Fort Wayne (Station 123037)

West Lafayette (Station 129430)

Figure 4.2.8 – Rainfall Estimates by Original and Modified Coefficients (contd.)

Station	Indianapolis (124259)		Evansville (122738)		Fort Wayne (123037)		West Lafayette (129430)	
Coefficient Type	Original	Modified	Original	Modified	Original	Modified	Original	Modified
Stdev of ε (inch)	0.250	0.164	0.181	0.235	0.126	0.144	0.295	0.167
Average of $ \xi $ (%)	5.078	3.160	7.566	4.409	6.577	3.621	6.911	4.085
r^2	0.9868	0.9828	0.9796	0.9738	0.9823	0.9838	0.9483	0.9634

Table 4.2.10 - Estimation Error Statistics of Four Stations
by Different Coefficient Type

4.2.3. Split Sample Test

To test the rainfall estimates from the revised 2nd order parameters, a split sample test is conducted. 20% of the data stations are removed from the data set. The remaining 80% data are used to estimate the parameters a_1 , b_1 , c_1 . Then, these parameters are used to estimate rainfall in the stations which were not used to estimate the parameters. The test is repeated several times, and the results are shown in Table 4.2.11. The estimated versus GEV values are plotted in Figure 4.2.9. For every test, stations with the highest and the lowest percentage absolute difference are picked and plotted in Figure 4.2.10. These results show that although different stations are removed every time, the statistics do not change too much. The results are consistent. Therefore, this test validates this method and demonstrates that the parameters are reliable.

The 2nd order coefficients established by this method are computed with the Chen's original coefficients, in Figure 4.2.11. The coefficients estimated are quite different with Chen's original coefficients. However, coefficients derived in the present study provide better answer for the Indiana data because of its higher r^2 values and by the results of split sample test. Therefore, they are recommended for use in Indiana.

Split Sample Test - Test1

Split Sample Test - Test2

Figure 4.2.9 – Split Sample Test

Split Sample Test - Test3

Split Sample Test - Test4

Figure 4.2.9 – Split Sample Test (contd.)

Figure 4.2.10 – Stations with the Highest and Lowest
Average $|\xi|$ of Split Sample Test

Split Sample Test2 - Station 127999
with the Highest Absolute Percentage Difference

Split Sample Test2 - Station 124497
with the Lowest Absolute Percentage Difference

Figure 4.2.10 – Stations with the Highest and Lowest
Average $|\xi|$ of Split Sample Test (contd.)

Split Sample Test3 - Station 125407
with the Highest Absolute Percentage Difference

Split Sample Test3 - Station 122825
with the Lowest Absolute Percentage Difference

Figure 4.2.10 – Stations with the Highest and Lowest

Average $|\xi|$ of Split Sample Test (contd.)

Split Sample Test4 - Station 124730
with the Highest Absolute Percentage Difference

Split Sample Test4 - Station 127959
with the Lowest Absolute Percentage Difference

Figure 4.2.10 – Stations with the Highest and Lowest

Average $|\xi|$ of Split Sample Test (contd.)

Figure 4.2.11 - Comparison of Chen's Original Coefficients and the 2nd Order Coefficients of Indiana Data

Test1		Test2		Test3		Test4	
Removed Station	Average $ \xi $ (%)	Removed Station	Average $ \xi $ (%)	Removed Station	Average $ \xi $ (%)	Removed Station	Average $ \xi $ (%)
120482	5.85	127999	6.76	125407	5.16	124730	4.87
127930	4.45	120482	6.01	127930	4.36	124908	3.62
122645	3.82	122738	4.40	124181	4.28	123062	3.58
120200	3.74	124181	4.06	127298	3.90	124372	3.26
128967	3.35	128967	3.45	122645	3.87	126056	3.23
127370	3.22	126056	3.29	122039	3.21	128967	2.88
121256	3.02	126705	3.13	121256	2.97	127069	2.78
124973	2.95	122161	3.02	124837	2.75	124973	2.76
121814	2.87	124837	2.92	128784	2.65	124356	2.59
127069	2.78	123206	2.50	129430	2.59	125535	2.18
123777	2.44	124286	2.40	124259	2.44	129174	2.04
124356	2.28	129174	2.27	121814	2.41	128187	2.04
126864	2.14	123091	1.77	126864	2.20	128036	1.84
128187	2.10	128999	1.28	128999	1.32	121739	1.54
128442	1.83	124497	1.12	122825	1.22	127959	1.44
Total	3.12	Total	3.23	Total	3.02	Total	2.71
r^2	0.9796	r^2	0.9767	r^2	0.9798	r^2	0.9812

Table 4.2.11 - Results of Split Sample Test

4.2.4. Consistency of Ratio R_T

In Chen's original method, R_{10} is used to represent all other return periods at the same station. This is based on the assumption that R_T values are close to each other for different return periods of T at the same station. However, Chen did not provide any evidence supporting this assumption.

In order to investigate the assumption that R_T does not vary with T , the ratio $R_T = P_1^T / P_{24}^T$ is calculated for every station by using the depths computed by GEV distribution. These R_T values are plotted against return period T as shown in Figure 4.2.12. As seen from Figure 4.2.12 for some stations, R_T values are close to each other for different return periods. Consequently, for such stations the same R_T value can be used for different return periods. However, for most stations, R_T values vary. The

The Average and Standard Deviation of R_T R_T Under Different Return Periods (I) Figure 4.2.12 - R_T Under Different Return Period T

R_T Under Different Return Periods (II) R_T Under Different Return Periods (III) Figure 4.2.12 - R_T Under Different Return Period T (contd.)

R_T Under Different Return Periods (IV) R_T Under Different Return Periods (V) Figure 4.2.12 - R_T Under Different Return Period T (contd.)

R_T Under Different Return Periods (VI) R_T Under Different Return Periods(VII) Figure 4.2.12 - R_T Under Different Return Period T (contd.)

R_T Under Different Return Periods (VIII) R_T Under Different Return Periods (IX) Figure 4.2.12 - R_T Under Different Return Period T (contd.)

difference for most stations is greater than 5%. Besides, R_T values varying for different stations are close to each other for small return periods, and become quite variable for longer return periods. The standard deviation increases with increasing return periods, which indicate that, for longer return periods, R_T values become more diverse.

Based on these results, it seems inappropriate to use R_{10} to represent other R_T values. To improve the accuracy, the maps of R_T for different T values were calculated and provided in Figure 4.2.13. The desired R_T value for their desired locations and return periods may be looked up from these maps. The coefficients a_1 , b_1 , and c_1 are computed by applying R_T into the 2nd order polynomial equation (Eq. 4.2.12 - 4.2.14). The resulting values are used to estimate the intensities for different return periods.

4.3. Intensity - Return Period Relationship

In this section, the intensity-return period relationship is discussed. Chen's intensity-return period formula is shown in Eq. 4.2.5. This formula is derived from Chow's (1953) theoretical relationship

$$P_t^T = \alpha \log T + \beta \quad (4.3.1)$$

where α , β are unknown coefficients. Use $T = 10$ year and $T = 100$ year into Eq. 4.3.1 to get Eq. 4.3.2 and 4.3.3

$$P_t^{100} = \alpha \log 100 + \beta = 2\alpha + \beta \quad (4.3.2)$$

$$P_t^{10} = \alpha \log 10 + \beta = \alpha + \beta \quad (4.3.3)$$

solve for α , β in terms of P_t^{100} and P_t^{10} to obtain

Spacing between Contours: 1

Figure 4.2.13 – Map of R_T – Return Period $T = 2$ Year

Spacing between Contours: 1

Figure 4.2.13 – Map of R_T – Return Period $T = 5$ Year (contd.)

Spacing between Contours: 1

Figure 4.2.13 – Map of R_T – Return Period $T = 10$ Year (contd.)

Spacing between Contours: 2

Figure 4.2.13 – Map of R_T – Return Period $T = 25$ Year (contd.)

Spacing between Contours: 2

Figure 4.2.13 – Map of R_T – Return Period $T = 50$ Year (contd.)

Spacing between Counters: 2

Figure 4.2.13 – Map of R_T – Return Period $T = 100$ Year (contd.)

$$\alpha = P_t^{100} - P_t^{10} = P_t^{10} \left(\frac{P_t^{100}}{P_t^{10}} - 1 \right) = P_t^{10} (x_t - 1) \quad (4.3.4)$$

$$\beta = 2P_t^{10} - P_t^{100} = P_t^{10} \left(2 - \frac{P_t^{100}}{P_t^{10}} \right) = P_t^{10} (2 - x_t) \quad (4.3.5)$$

Where $x_t = P_t^{100} / P_t^{10}$. Substitute α and β in Eq. 4.3.4 and 4.3.5 into Eq. 4.3.1

and divide each side by P_t^{10} . To obtain

$$\frac{P_t^T}{P_t^{10}} = (x_t - 1) \log T + (2 - x_t) = \log T^{(x_t-1)} + \log 10^{(2-x_t)} = \log 10^{(2-x_t)} T^{(x_t-1)} \quad (4.3.6)$$

Also, P_t^T / P_t^{10} is equal to i_t^T / i_t^{10} .

$$\frac{P_t^T}{P_t^{10}} = \frac{(i_t^T / t)}{(i_t^{10} / t)} = \frac{i_t^T}{i_t^{10}} = \log 10^{(2-x_t)} T^{(x_t-1)} \quad (4.3.7)$$

Hence, we get intensity-return period formula in (Eq. 4.2.5). This relationship is tested by using the Indiana data.

4.3.1. Test of the Intensity - Return Period Relationship

Similar to the procedure in section 4.2.1, GEV rainfall is used to examine the validity of the intensity-return period relationship. The 10-year and 100-year GEV rainfall intensity P_t^{10} and P_t^{100} are used in Eq 4.2.5 to estimate the 2-year, 5-year, 25-year, and 50-year intensities. An example is shown below:

Example 4.3.1. Example of Computation of Intensity - Return Period Relationship

For station 120132, the 10-year and 100-year GEV rainfall intensities are used to evaluate x_t . Then Eq. 4.2.5 is used to estimate the 2-year, 5-year, 25-year, and 50-year

rainfall intensities. Let us consider the 2-hour rainfall as example.

For $t = 2$ hour:

$$x_2 = P_2^{100} / P_2^{10} = i_2^{100} / i_2^{10} = 1.658 / 1.196 = 1.386$$

$$i_2^2 = i_2^{10} \log(10^{(2-x_2)} 2^{(x_2-1)}) = 1.196 * \log(10^{(2-1.386)} 2^{(1.386-1)}) = 0.874 \text{ inch/hour}$$

$$i_2^5 = i_2^{10} \log(10^{(2-x_2)} 5^{(x_2-1)}) = 1.196 * \log(10^{(2-1.386)} 5^{(1.386-1)}) = 1.057 \text{ inch/hour}$$

$$i_2^{25} = i_2^{10} \log(10^{(2-x_2)} 25^{(x_2-1)}) = 1.196 * \log(10^{(2-1.386)} 25^{(1.386-1)}) = 1.380 \text{ inch/hour}$$

$$i_2^{50} = i_2^{10} \log(10^{(2-x_2)} 50^{(x_2-1)}) = 1.196 * \log(10^{(2-1.386)} 50^{(1.386-1)}) = 1.519 \text{ inch/hour}$$

Detailed results are shown in Table 4.3.1:

	Return Periods (year)		x_t	Return Periods (year)			
	10	100		2	5	25	50
i_1^T (inch/hour)	1.745	2.605	1.493	1.143	1.486	2.087	2.346
i_2^T (inch/hour)	1.196	1.658	1.386	0.874	1.057	1.380	1.519
i_3^T (inch/hour)	0.889	1.238	1.393	0.645	0.784	1.028	1.133
i_4^T (inch/hour)	0.702	1.015	1.446	0.483	0.608	0.826	0.921
i_6^T (inch/hour)	0.503	0.739	1.469	0.338	0.432	0.597	0.668
i_{12}^T (inch/hour)	0.283	0.388	1.372	0.209	0.251	0.325	0.356
i_{18}^T (inch/hour)	0.206	0.290	1.411	0.147	0.180	0.239	0.265
i_{24}^T (inch/hour)	0.162	0.228	1.406	0.116	0.143	0.189	0.209

Table 4.3.1 - Test of the Intensity - Return Period Relationship of Station 120132

These and similar results are plotted against GEV values of all Indiana stations in Figure 4.3.1. The statistics of estimation error are shown in Table 4.3.2. Because this relationship is based on known P_t^{10} and P_t^{100} , only the results corresponding to 2yr, 5yr, 25yr, and 50yr return periods are discussed. From these results we can observe that, the relationship is good in estimating intensity for longer return periods, such as 25-year and

Intensity - Return Period Test - Overall Result

Figure 4.3.1 – Intensity – Return Period Behavior

50-year rainfall, but is not as good for shorter return periods, such as 2-year and 5-year. Especially for 2-year estimates, the error is the highest, and the r^2 is the lowest. However, the problem is not serious because the standard deviation of these errors is 0.197 inch, which is not high. Besides that, 2-year rainfall are small events and are not as important as higher return period events. To conclude, the intensity-return period relationship is acceptable for the Indiana data.

Return Period (year)	2	5	25	50	Overall
Stdev of ε (inch)	0.197	0.064	0.041	0.037	0.118
Average of $ \xi $ (%)	8.409	1.773	0.727	0.567	2.869
r^2	0.8528	0.9872	0.9978	0.9988	0.9898

Table 4.3.2 - Statistics of Evaluation of Chen's Intensity - Return Period Relationship

4.3.2. Test of Consistency x_t

x_1 is assumed by Chen not to vary with time t . To examine this assumption, x_t under different stations and durations are calculated and plotted in Figure 4.3.2. The results from this figure show that although for some stations, x_t changes a lot, but for most of the stations, x_t does not vary significantly. The average is almost the same and the standard deviation remains in a similar range throughout all different durations. Consequently, the assumption that x_t does not change significantly with t is acceptable.

4.3.3. Combination of Intensity - Duration - Return Period Relationship

From the previous discussion, two suggestions are made for the estimation of Indiana rainfall data. One is that the maps of R_T of different return period should be

The Average and Standard Deviation of x_t x_t Under Different Durations (I) Figure 4.3.2 - x_t Under Different Durations

Figure 4.3.2 - x_t Under Different Durations (contd.)

Figure 4.3.2 - x_t Under Different Durations (contd.)

x_t Under Different Durations (VI) x_t Under Different Durations (VII) Figure 4.3.2 - x_t Under Different Durations (contd.)

x_t Under Different Durations (VIII) x_t Under Different Durations (IX) Figure 4.3.2 - x_t Under Different Durations (contd.)

used; the other is that Chen's coefficients a_1 , b_1 , c_1 must be estimated by 2nd order polynomial equation. These procedures were evaluated by using Indiana data. These results from Chen's original coefficients by TP-40 ratios are shown in Figure 4.3.3. Also, the modified result versus GEV value in Figure 4.3.4. The statistics of estimation error are presented in Table 4.3.3.

Coefficients Type	Original	Modified
Stdev of ε (inch)	0.482	0.228
Average of $ \xi $ (%)	9.183	4.651
r^2	0.8488	0.9680

Table 4.3.3 - Comparison of Estimates by Original and Modified Coefficients

The standard deviation decreases from 0.482 inch to 0.228 inch, the average absolute percentage error decreases from 9.183 to 4.651, and the r^2 increases from 0.8488 to 0.9680. The modified coefficients improve the estimates. Thus, the revised procedure is acceptable. Example 4.3.1 below illustrates the method for using the revised procedure.

Figure 4.3.3 – GEV vs. Chen's Original Estimates

Figure 4.3.4 – GEV vs. Modified Estimates

Example 4.3.2. Revised Method with Modified Coefficients

Estimate the i-d-f curve for Indianapolis. In this example, 2, 5, 10, 25, 50, 100 year and 1, 2, 3, 4, 6, 8, 12, 18, 24 hour intensities are computed using revised method. 10-year, 1-hour GEV rainfall depth $P_1^{10} = 1.80$ inch, 100-year, 1-hour GEV rainfall depth $P_1^{100} = 2.51$ inch are given to solve this question.

STEP 1 - Look up known depth

Obtain: The 10-year, 1-hour rainfall depth, P_1^{10}

The 100-year, 1-hour rainfall depth, P_1^{100}

The location is nearby Station 124286. Hence, use the rainfall depth of Station 124286:

$$P_1^{10} = 1.80 \text{ inch}$$

$$P_1^{100} = 2.51 \text{ inch}$$

STEP 2 - Compute ratio x_1

$$x_1 = P_1^{10} / P_1^{100} = 1.394$$

By Chen's assumption, x_t does not vary significantly with duration t , thus:

$$x_t = x_1 = 1.394$$

STEP 3 - Read of R_T from figure 4.2.14

From figure 4.2.14, read the value of R_T for the city of Indianapolis.

T (year)	2	5	10	25	50	100
R_T (%)	41.4	45.2	47.3	50.5	52.5	54.5

STEP 4 - Compute a_1 , b_1 , c_1

Use the Eq. 4.2.12-14 with the coefficients provided in Table 4.2.8.

T (year)	2	5	10	25	50	100
$a_1(T)$	37.62	38.32	39.37	41.88	44.02	46.58
$b_1(T)$	26.83	21.06	19.03	17.54	17.59	18.39
$c_1(T)$	0.813	0.827	0.836	0.852	0.863	0.875

STEP 5 - Intensity i_1^{10}

$$i_1^{10} = P_1^{10} = 1.80 \text{ inch}$$

STEP 6 - Compute the intensity i_t^T

$$i_t^T = \frac{i_1^{10} a_1(T) \log(10^{(2-x_t)} T^{(x_t-1)})}{(60t + b_1(T))^{c_1(T)}}$$

Result: i_t^T (inch/hour)

Duration	T (year)					
(hour)	2	5	10	25	50	100
1	1.301	1.605	1.836	2.143	2.365	2.571
2	0.849	1.015	1.145	1.315	1.442	1.564
3	0.642	0.757	0.848	0.966	1.055	1.141
4	0.522	0.610	0.681	0.771	0.839	0.905
6	0.386	0.446	0.495	0.557	0.603	0.648
8	0.310	0.356	0.393	0.440	0.476	0.510
12	0.226	0.257	0.283	0.315	0.339	0.361
18	0.164	0.186	0.203	0.224	0.240	0.255
24	0.131	0.147	0.160	0.176	0.188	0.199

GEV intensity

Duration	T (year)					
(hour)	2	5	10	25	50	100
1	1.105	1.540	1.803	2.110	2.320	2.515
2	0.687	0.975	1.162	1.394	1.563	1.728
3	0.506	0.712	0.846	1.012	1.134	1.253
4	0.410	0.577	0.688	0.826	0.929	1.031
6	0.310	0.429	0.505	0.598	0.664	0.728
8	0.254	0.343	0.398	0.463	0.507	0.549
12	0.191	0.252	0.286	0.323	0.347	0.367
18	0.140	0.182	0.205	0.228	0.242	0.253
24	0.111	0.142	0.158	0.174	0.183	0.191

Figure 4.3.5 – Estimated Depth vs. GEV Depth in Example 4.3.2

V. Variability in Rainfall Estimates

5.1. Introduction and Data Collection

For practicing engineers, it is important to know the estimated rainfall depth or intensity when designing an engineering structure. However, it is not necessary to perform frequency analysis every time. Therefore, looking up the rainfall values from data sources is the usual method used by practitioners. There are several rainfall estimates which may be used in Indiana, such as NOAA's National Weather Service (NWS) rainfall, Indiana Department of Natural Resources (DNR) rainfall, and Huff-Angel rainfall (1992). They are based on different data and analysis procedures and some of them have quite different estimated values. Often, estimates from different sources are quite different. Therefore, it is important to know these differences. In this study, these three rainfall estimates are compared to the Generalized Extreme Value (GEV) rainfall estimate, which is discussed in Chapter 3. Before proceeding with the comparison, the three rainfall estimates are discussed below.

NWS rainfall can be obtained from NOAA Atlas 14 from NOAA's National Weather Service Precipitation Frequency Data Server, <http://hdsc.nws.noaa.gov/hdsc/pfds/>, which is the latest version of rainfall estimate provided by NWS. It is a regionalized rainfall estimate based on L-moment algorithm (Hosking and Wallis, 1997). NWS provides a user-friendly web interface. By selecting the location of interest from an interactive map of Indiana in the webpage, the latest NWS rainfall can be obtained, as in the example shown in Figure 5.1.1. The confidence band of estimates is also provided. Rainfall estimates with durations of 5min, 10min, 15min, 30min, 1hr, 2hr, 3hr, 6hr, 12hr, 24hr, 48hr, 4day, 7day, 10day, 20day, 30day, 45day, 60day, and return periods of 2yr, 5yr, 10yr, 25yr, 50yr, 100yr, 200yr, 500yr, 1000yr are provided. In this study, NWS rainfall

ARI* (years)	5 min	10 min	15 min	30 min	60 min	120 min	3 hr	6 hr	12 hr	24 hr	48 hr	4 day	7 day	10 day	20 day	30 day	45 day	60 day
2	0.46	0.71	0.87	1.17	1.43	1.67	1.77	2.11	2.48	2.90	3.39	3.85	4.54	5.16	7.05	8.71	11.02	13.22
5	0.54	0.83	1.02	1.40	1.76	2.05	2.17	2.58	3.02	3.53	4.12	4.64	5.46	6.17	8.31	10.13	12.71	15.15
10	0.60	0.92	1.13	1.57	2.00	2.34	2.48	2.95	3.45	4.03	4.68	5.25	6.18	6.98	9.30	11.23	14.00	16.63
25	0.67	1.02	1.26	1.78	2.31	2.72	2.90	3.45	3.99	4.69	5.42	6.07	7.16	8.07	10.61	12.66	15.66	18.55
50	0.72	1.09	1.35	1.93	2.55	3.00	3.23	3.84	4.43	5.21	6.00	6.72	7.93	8.92	11.62	13.75	16.91	19.97
100	0.77	1.16	1.44	2.08	2.78	3.29	3.56	4.23	4.85	5.72	6.59	7.36	8.72	9.79	12.62	14.82	18.10	21.33
200	0.82	1.22	1.51	2.21	3.00	3.58	3.89	4.62	5.28	6.25	7.16	8.01	9.51	10.67	13.61	15.86	19.24	22.65
500	0.88	1.29	1.61	2.38	3.29	3.94	4.33	5.15	5.84	6.95	7.93	8.86	10.59	11.84	14.90	17.22	20.68	24.30
1000	0.92	1.33	1.67	2.50	3.50	4.22	4.67	5.56	6.27	7.48	8.52	9.51	11.41	12.75	15.87	18.23	21.73	25.50

Partial duration based Point Precipitation Frequency Estimates Version: 2
39.5736 N 85.1583 W 800 ft

Figure 5.1.1 - Example of Obtaining NWS Rainfall

information used for comparison was collected up to mid March, 2005.

DNR rainfall can be obtained from Indiana Department of Natural Resources' Website (http://www.in.gov/dnr/water/surface_water/rainfallfrequency/). Actually, it is adopted from Hydro-35 and TP-40, which are both important rainfall estimates in recent decades. The reason to combine them is that TP-40 values are better for longer, and Hydro-35 are better for shorter durations. Therefore, for durations of 1hr or less, it is adopted from Hydro-35, and for longer durations, it is adopted from TP-40.

For duration of 1hr or shorter, maps are provided for 2yr and 100yr rainfall estimates. To get the estimates with return periods in between, the following formulas are used.

For durations less than 1 hour:

$$5\text{yr rainfall} = 0.278 (100\text{yr rainfall}) + 0.674 (2\text{yr rainfall}) \quad (5.1.1)$$

$$10\text{yr rainfall} = 0.449 (100\text{yr rainfall}) + 0.496 (2\text{yr rainfall}) \quad (5.1.2)$$

$$25\text{yr rainfall} = 0.669 (100\text{yr rainfall}) + 0.293 (2\text{yr rainfall}) \quad (5.1.3)$$

$$50\text{yr rainfall} = 0.835 (100\text{yr rainfall}) + 0.146 (2\text{yr rainfall}) \quad (5.1.4)$$

For the comparison, 1hr-2yr and 1hr-100yr rainfall are obtained directly from the maps. 1hr-5yr, 10yr, 25yr, 50yr rainfalls are estimated by eqs. 5.1.1. - 5.1.4.

For longer durations, maps of durations of 2hr, 3hr, 6hr, 12hr, 24hr, 2day, 4day, 7day, 10day and return periods of 1yr, 2yr, 5yr, 10yr, 25yr, 50yr, 100yr are given. In this study, DNR estimates for rainfall stations in Indiana are looked up. Example of DNR rainfall is shown in Figure 5.1.2.

Huff-Angel rainfall are provided by Huff and Angel (1992). It covers several states in the mid-west. Rainfall estimates with durations of 5 min, 10min, 15min, 30min, 1hr, the entire state is divided into 9 rainfall regions. For all the stations in a region, the same estimates apply. Example of Huff-Angel rainfall is shown in Figure 5.1.3.

Figure 5.1.2 - Example of DNR Rainfall Obtaining

**Sectional Mean Frequency Distributions for Storm Periods of 5 Minutes to 10 Days
and Recurrence Intervals of 2 Months to 100 Years in Indiana**

Sectional code (see figure 1 on page 4)

01 - Northwes 06 - East Central
02 - North Central 07 - Southwest
03 - Northeast 08 - South Central
04 - West Central 09 - Southeast
05 - Central

Rainfall (inches) for given recurrence interval

Section	Duration	2-month	3-month	4-month	6-month	9-month	1-year	2-year	5-year	10-year	25-year	50-year	100-year
01	10-day	2.07	2.50	2.88	3.38	3.89	4.23	4.84	5.79	6.67	8.03	9.23	10.58
01	5-day	1.68	2.01	2.27	2.63	3.03	3.29	3.84	4.70	5.50	6.81	7.99	9.37
01	72-hr	1.53	1.80	2.04	2.36	2.71	2.95	3.46	4.24	4.97	6.10	7.17	8.38
01	48-hr	1.40	1.64	1.83	2.12	2.44	2.65	3.12	3.87	4.56	5.58	6.52	7.58
01	24-hr	1.33	1.55	1.69	1.96	2.23	2.42	2.89	3.61	4.22	5.22	6.10	7.12
01	18-hr	1.25	1.45	1.59	1.84	2.09	2.27	2.72	3.39	3.97	4.91	5.73	6.69
01	12-hr	1.16	1.35	1.48	1.71	1.94	2.11	2.51	3.14	3.67	4.54	5.31	6.19
01	6-hr	1.00	1.16	1.27	1.47	1.67	1.82	2.17	2.71	3.16	3.91	4.57	5.34
01	3-hr	0.85	0.99	1.08	1.26	1.43	1.55	1.85	2.31	2.70	3.34	3.90	4.56
01	2-hr	0.77	0.90	0.98	1.13	1.29	1.40	1.68	2.09	2.45	3.03	3.54	4.13
01	1-hr	0.63	0.73	0.80	0.92	1.05	1.14	1.36	1.70	1.98	2.45	2.87	3.35
01	30-min	0.50	0.58	0.63	0.73	0.83	0.90	1.07	1.34	1.56	1.93	2.26	2.63
01	15-min	0.36	0.42	0.45	0.53	0.60	0.65	0.78	0.97	1.14	1.41	1.65	1.92
01	10-min	0.28	0.33	0.36	0.41	0.47	0.51	0.61	0.76	0.89	1.10	1.28	1.50
01	5-min	0.16	0.19	0.20	0.23	0.27	0.29	0.35	0.43	0.51	0.63	0.73	0.85

Figure 5.1.3 - Example of Huff-Angel Rainfall Obtaining

5.2. Comparison of Rainfall Estimates

To compare these rainfall estimates in Indiana, two measures are used. Rainfall depth difference and percentage difference between source A and source B is defined as

$\varepsilon_{A,B}$ and $\xi_{A,B}$:

$$\varepsilon_{A,B} = (\text{rainfall depth of source A}) - (\text{rainfall depth of source B}) \quad (5.2.1)$$

$$\xi_{A,B} = ((\text{depth of source A}) - (\text{depth of source B})) / (\text{depth of source B}) \quad (5.2.2)$$

Also, similar to the comparison procedure in Chapter 4, the standard deviation of ε , the absolute percentage difference $|\xi|$, and the coefficient of determination r^2 are calculated. When calculating the regression line, intercept is set to 0. The reason for this additional constraint is that it is interesting to know generally, how rainfall depths of sources A and B compare with each other. By setting intercept to zero, we can make such judgments by using the slope. For example, for the regression line (depth B) = k *(depth A), if $k > 1$, then depth B is generally larger than depth A and vice versa.

As GEV rainfall is the at-site estimate, results are obtained at the location of stations. To compare, rainfall values NWS, DNR, and Huff-Angel rainfalls in every station location is looked up. Rainfall estimates with durations of 1hr, 2hr, 3hr, 6hr, 12hr, 24hr, and return periods of 2yr, 5yr, 10yr, 25yr, 50yr, 100yr are used for the comparison. The standard deviation of difference is shown in Table 5.2.1, the average absolute percentage difference is shown in table 5.2.2, and the coefficient of determination is shown in Table 5.2.3. Also, each pairs of rainfall are plotted in Figure 5.2.1.

Standard Deviation of Difference: $\varepsilon_{A,B}$ (unit: inch)

Source B	Source A			
	GEV	NWS	DNR	H&A
GEV		0.361	0.397	0.433
NWS	0.361		0.282	0.219
DNR	0.397	0.282		0.330
H&A	0.433	0.219	0.330	

Table 5.2.1 - Standard Deviation of Difference ε

Figure 5.2.1 - Comparison of Different Rainfalls

Average of Absolute Difference: $|\xi_{A,B}|$ (unit: %)

Source B	Source A			
	GEV	NWS	DNR	H&A
GEV		9.109	10.954	12.112
NWS	10.598		6.454	5.965
DNR	12.587	6.384		6.841
H&A	14.810	6.408	7.406	

Table 5.2.2 - Average of Absolute Difference $|\xi|$

Coefficient of Determination

Source B	Source A			
	GEV	NWS	DNR	H&A
GEV		0.9105	0.8480	0.8849
NWS	0.9105		0.9423	0.9740
DNR	0.8480	0.9423		0.9399
H&A	0.8849	0.9740	0.9399	

Table 5.2.3 - Coefficient of Determination r^2

Overall, compared to the GEV estimates H&A estimates rainfall depth highest. NWS and DNR are in between. It can be seen that GEV is more different than others. It is reasonable because GEV rainfall is the station estimate, and is not based on any regional method. On the other hand, the other three rainfalls are regional estimates, and such estimates had been smoothened by regional data with homogeneous assumption. Hence, higher difference in estimates is to be anticipated.

Besides that, GEV rainfall is calculated for every station with long term observations. Statistically, it is the most reliable estimate. Therefore, the comparison to GEV can illustrate as the indicator of goodness of the regionalization method. The closer to at-site GEV, the better the regional rainfall is.

The statistics show that NWS is close to GEV with the lowest difference, and DNR is the second lowest one. It means that the NWS data is better regionalized than TP-40

and Hydro-35. In this aspect, Huff-Angel estimates are poor because the difference with GEV is the highest. It can be recalled that Huff and Angel merely divided the entire Indiana into nine rainfall regions. It is obviously not a good procedure.

As for the three regional rainfalls estimates, NWS estimate is higher than DNR estimate and lower than Huff-Angel estimate. Huff-Angel estimate is the largest compared to others. Therefore, using Huff-Angel estimate may cause serious overestimation.

Further examination seems necessary for Huff-Angel rainfall estimate. For Huff-Angel's study, they simply investigated daily rainfall data. For durations other than 24hr, a simple constant ratio is applied to do conversion, ratios shown in Table 5.2.4. For example, 1hr rainfall to 24hr rainfall is always 0.47; so if the 24hr rainfall depth is 5 inch, then the 1hr rainfall depth is simply $5 \times 0.47 = 2.35$ inch. This assumption is quite simple and easy to use. However, the validity of this important assumption is tested.

Average Ratio of X-Hour/24-Hour Rainfall	
<i>Rain period (hours)</i>	<i>Ratio (x-hour/24-hour)</i>
18	0.94
12	0.87
6	0.75
3	0.64
2	0.58
1	0.47
0.50 (30 min.)	0.37
0.25 (15 min.)	0.27
0.17 (10 min.)	0.21
0.08 (5 min.)	0.12

Table 5.2.4 – Huff-Angel's Ratio to Calculate Durations Other Than 24hr

In order to test this assumption, 20 nearby stations within a 100km radius were selected. The ratio is calculated and plotted by using GEV estimates for different return periods, as shown in Figure 5.2.2. From these figures, it is seen that Huff-Angel's ratio only an average. The ratio will become more diverse with increasing return periods. The standard deviation increases when return period increases. Consequently, the ratio approach seems to be not applicable. A similar plot by using NWS data is shown in Figure 5.2.3. The variability becomes smaller because NWS estimate is regional. However, it is not possible to say that constant ratio assumption is appropriate, especially for high return periods.

Figure 5.2.2 - Ratio Test Using GEV Rainfall

Figure 5.2.2 - Ratio Test Using GEV Rainfall (contd.)

Figure 5.2.2 - Ratio Test Using GEV Rainfall (contd.)

Figure 5.2.2 - Ratio Test Using GEV Rainfall (contd.)

Figure 5.2.2 - Ratio Test Using GEV Rainfall (contd.)

Figure 5.2.3 - Ratio Test Using NWS Rainfall

Figure 5.2.3 - Ratio Test Using NWS Rainfall (contd.)

Figure 5.2.3 - Ratio Test Using NWS Rainfall (contd.)

Figure 5.2.3 - Ratio Test Using NWS Rainfall (contd.)

Figure 5.2.3 - Ratio Test Using NWS Rainfall (contd.)

VI. Huff Distribution for Indiana

6.1. Introduction to Huff Distribution

In previous sections, the topic of investigation was the magnitude of rainfall. However, besides rainfall depth, the temporal distribution of rainfall is also of great importance, especially in planning, sizing and design of stormwater management systems. In this chapter, the temporal distribution of Indiana rainfall is investigated. Huff distribution is selected for analysis.

Huff (1967) described the temporal distribution of rainfall by its probabilistic nature. His study was performed by using data collected with 40 rain gages. These raingages are distributed over a 400 square mile area in east-central Illinois. Huff found that the major portion of the total storm rainfall occurs in a small duration of the total storm duration. The storms were classified as belonging to four groups (1st, 2nd, 3rd, and 4th quartiles) depending on the quartile, defined as a 25% time segment of the total storm duration, in which the greatest amount of total rainfall occurs. Huff's 2nd quartile distribution is shown as an example in Figure 6.1.1.

Generally, in practice, the 1st quartile Huff distribution is used for storms less than or equal to 6 hours in duration, while the 2nd quartile for storm duration greater than 6 hours and less than or equal to 12 hours, the 3rd quartile for storm duration greater than 12 hours and less than or equal to 24 hours, and the 4th quartile storm for storm duration greater than 24 hours (IDOT DWR, 1992).

Huff's methodology is reliable because it is based on the historical rainfall records. Huff gathered the historical events, transformed them into dimensionless form, classified them by quartile, and calculated the values for every 10% of time such a storm occurs. Hence, Huff distribution should be able to represent the statistical features of the temporal

rainfall for the study area. In the following sections, Huff distribution will be estimated by using the Indiana rainfall data. First, the data from single rainfall stations will be analyzed. After that, regional comparison is conducted to see if a representative Huff distribution can be used for several nearby stations, and even for the entire state.

Figure 6.1.1 - Huff's 2nd Quartile Distribution

6.2. Data Collection

Hourly precipitation data from 74 stations mentioned in Chapter 2 is used for analysis. For these data, rainfall depth is recorded in hours when the observation is not zero. To proceed to the following temporal rainfall distribution analysis, the data are ordered by rainfall events. Hence, a criterion is decided to separate them. In this study, records with intervals greater or equal to 10 hours, in which observed rainfall depth is less than or equal to 0.01 inch, are regarded as two different events. With this criterion, observed events with various rainfall durations are obtained. An example of results of this

classification is shown in Table 6.2.1 and Figure 6.2.1 for station 120132. For this station, the longest rainfall lasted for 80 hours in the past fifty-five years. It can be observed that when the duration increases, the number of observed events decreases exponentially. Because the minimum unit duration adopted in this study is 1 hour, short duration rainfall is not suitable for analysis. Therefore, events with duration less than or equal to 3 hours are omitted.

Duration (hour)	Number of Events	Duration (hour)	Number of Events	Duration (hour)	Number of Events	Duration (hour)	Number of Events
1	1231	16	62	30	15	44	3
2	516	17	71	31	9	45	1
3	349	18	59	32	10	46	1
4	304	19	38	33	3	47	3
5	232	20	28	34	4	48	2
6	219	21	38	35	7	49	1
7	183	22	40	36	3	50	1
8	199	23	30	37	3	51	1
9	147	24	23	38	3	53	1
10	155	25	20	39	5	55	1
11	143	26	26	40	1	56	1
12	105	27	19	41	3	60	1
13	104	28	10	42	5	63	1
14	87	29	13	43	2	80	1
15	71						

Table 6.2.1 - Number of Observed Events of Station 120132

Figure 6.2.1 - Duration vs. Number of Events of Station 120132

6.3. Huff Distribution for a Single Station

The records of rainfall adopted in this study are greater than twenty-five years, even greater than fifty years for the most part. In fact, these recorded periods are much longer than the data used by Huff. Hence, it is sufficient for us to produce Huff curve for every single station without combining data from different nearby stations. In this section, Huff distributions of single stations are discussed.

Every rainfall event is separated with dimensions of hour and inch. Interpolation is used to change every event to dimensionless values in terms of percentage total time and depth. That is, for time axis, hour is changed to percentage total storm time, such as 10%, 20%....etc. For depth axis, rainfall depth is also changed to percentage accumulated rainfall.

After these events are transformed to dimensionless plots, they are classified into four quartiles by the maximum storm depth. If the maximum rainfall of an event happens to be in the first 25% time interval (0-25% of the total rainfall time), this event is classified into the 1st quartile rainfall. Similarly, if the maximum rainfall happens in the second 25% time interval (25-50% of the total rainfall time), it is the 2nd quartile rainfall, third 25% time interval (50-75%) for 3rd quartile, and fourth 25% time interval (75-100%) for 4th quartile. The properties of rainfall in each quartile should be similar.

Next, for each quartile, for every 10% time interval, statistical properties are found. That is, these accumulated rainfall percentages are arranged by order. For the largest 10% rainfall, an average percentage curve is obtained, denoted as the 10% Huff curve. For the next largest 10% rainfall, the average percentage is obtained as the 20% Huff curve. These curves are generated at 10% intervals. The Huff curves of station 120132 are shown in Figure 6.3.1, and ordinates are given in Table 6.3.1.

Figure 6.3.1 - Huff Curves of Station 120132

%StormTime	10% Huff Curve Ordinates				20% Huff Curve Ordinates				30% Huff Curve Ordinates			
	1st-Quartile	2nd-Quartile	3rd-Quartile	4th-Quartile	1st-Quartile	2nd-Quartile	3rd-Quartile	4th-Quartile	1st-Quartile	2nd-Quartile	3rd-Quartile	4th-Quartile
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	45.30	16.87	16.87	22.62	35.31	13.66	12.47	18.27	30.20	11.76	10.47	15.54
20	66.46	27.01	24.50	32.49	55.60	23.59	20.89	26.66	50.06	20.70	18.51	22.48
30	76.78	44.57	31.91	37.87	68.10	39.40	27.96	33.05	61.40	36.03	25.35	29.12
40	82.43	69.40	39.77	42.81	75.24	62.30	35.65	37.62	69.15	57.94	32.32	33.91
50	86.73	84.35	49.27	47.57	80.18	79.54	46.02	42.79	74.76	74.48	42.55	38.70
60	89.00	88.97	70.74	52.50	83.70	85.31	64.83	47.84	78.41	82.01	60.51	43.62
70	91.11	92.42	86.65	59.60	87.06	89.37	81.48	53.73	82.67	86.56	77.91	49.89
80	93.56	94.87	93.77	73.16	90.19	92.86	91.36	68.47	87.38	90.95	89.57	64.56
90	96.10	97.30	97.11	91.34	94.22	96.14	95.94	87.91	92.40	95.17	94.89	84.84
100	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

%StormTime	40% Huff Curve Ordinates				50% Huff Curve Ordinates				60% Huff Curve Ordinates			
	1st-Quartile	2nd-Quartile	3rd-Quartile	4th-Quartile	1st-Quartile	2nd-Quartile	3rd-Quartile	4th-Quartile	1st-Quartile	2nd-Quartile	3rd-Quartile	4th-Quartile
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	25.72	10.11	8.87	12.99	22.35	8.47	7.71	11.03	19.50	7.49	6.67	9.05
20	46.69	18.81	16.33	20.23	40.89	16.88	14.64	17.74	37.25	15.53	12.53	15.41
30	56.24	33.30	22.77	25.59	50.94	30.28	20.40	22.32	49.97	27.87	18.17	19.71
40	64.31	53.50	29.47	30.79	59.02	49.30	26.48	26.70	53.44	46.44	24.09	22.94
50	68.91	69.76	39.51	34.54	65.41	65.64	36.14	31.93	60.60	62.69	32.84	27.60
60	74.39	78.37	56.76	39.79	70.01	75.70	52.88	35.36	66.67	73.51	48.60	32.16
70	78.75	84.15	75.21	46.29	75.07	82.11	71.97	42.23	71.61	79.82	68.32	37.71
80	84.23	89.17	87.22	60.54	80.48	87.04	84.93	56.90	76.49	85.16	82.87	51.63
90	90.46	94.17	93.77	82.64	88.42	93.18	92.63	79.98	85.81	91.84	91.32	76.79
100	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

%StormTime	70% Huff Curve Ordinates				80% Huff Curve Ordinates				90% Huff Curve Ordinates			
	1st-Quartile	2nd-Quartile	3rd-Quartile	4th-Quartile	1st-Quartile	2nd-Quartile	3rd-Quartile	4th-Quartile	1st-Quartile	2nd-Quartile	3rd-Quartile	4th-Quartile
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	16.47	6.37	5.50	7.43	13.73	5.03	4.14	5.90	10.66	3.74	2.79	4.07
20	33.66	13.38	10.60	12.86	30.92	11.02	8.29	9.74	26.57	7.79	5.62	6.46
30	46.71	25.59	15.39	16.65	41.68	22.64	12.73	13.13	35.99	17.88	8.99	8.40
40	50.00	43.12	21.06	19.78	49.36	38.07	17.45	16.13	43.14	33.40	12.61	10.95
50	55.39	60.19	28.36	23.12	50.04	56.43	23.48	18.79	49.46	51.55	17.24	12.57
60	62.73	70.29	43.82	27.09	56.63	66.55	39.50	21.23	50.00	62.65	31.97	15.09
70	67.22	76.76	64.98	32.92	63.77	73.95	61.21	27.00	52.56	68.68	55.17	19.30
80	73.05	83.18	80.21	46.52	67.03	80.46	77.38	38.55	57.81	77.07	74.11	28.24
90	81.67	90.31	89.64	71.94	77.17	88.10	87.39	65.08	70.35	84.90	83.98	52.01
100	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 6.3.1 - Huff Curve Ordinates of Station 120132

6.4. Regional Huff Distribution

Next, regional Huff curves are calculated. Intuitively, for nearby stations, the Huff curves should be similar. For this analysis, the State of Indiana is divided into three regions as northern, mid and southern Indiana. The division of the state is shown in Figure 6.4.1. For each region and for the entire state, the average of Huff ordinates is calculated, and the average Huff curves are shown in Figure 6.4.2. From this figure, it can be seen that for the 2nd, 3rd, and 4th quartile Huff distributions, these distributions are close to each other. For the 1st quartile Huff distribution, though there is some difference, it is not very large. The average and standard deviation of Huff ordinates of all the stations is shown in Figure 6.4.3. A similar result is shown that for the 2nd, 3rd, and 4th quartile Huff distribution, the ordinates are close to each other. For the 1st quartile, there are higher standard deviations for some ordinates, but it is not very much. Hence, Huff curves from different stations are quite similar. For practical use, the average Huff curve of all stations in Indiana can be used as the representative Huff curve of Indiana. This is another evidence showing that the rainfall in Indiana is quite homogeneous. Hence, a single probability density function and temporal rainfall distribution can be used to describe the rainfall properties. The final average Huff distribution is shown in Figure 6.4.4, and the values are shown in Table 6.4.1.

To facilitate the computational purpose, a regression model is fitted for every Huff curves shown in Figure 6.4.4. The regression model is in the following form:

$$P(S) = H_1 S + H_2 S^2 + \dots + H_{10} S^{10} \quad (6.4.1)$$

where S is the percentage of storm time, from 0 to 100; P is the percentage of precipitation, which is a function of S , from 0 to 100; H_j is the j -th regression

coefficient, shown in Table 6.4.2. Eq. 6.4.1 offers users an easier way to calculate Huff curve coordinates without interpolating data from Table 6.4.1. These fitted Huff curves are shown in Figure 6.4.5.

Figure 6.4.1 - Regions of Indiana of Regional Analysis of Huff Distribution

Figure 6.4.2 - Average Huff Curves for Each Region and Indiana

Figure 6.4.2 - Average Huff Curves for Each Region and Indiana (contd.)

Figure 6.4.2 - Average Huff Curves for Each Region and Indiana (contd.)

Figure 6.4.2 - Average Huff Curves for Each Region and Indiana (contd.)

Figure 6.4.3 - Mean and Stdev of the 1st Quartile Huff Distribution for Indiana

Figure 6.4.3 - Mean and Stdev of the 2nd Quartile Huff Distribution for Indiana

Figure 6.4.3 - Mean and Stdev of the 3rd Quartile Huff Distribution for Indiana

Figure 6.4.3 - Mean and Stdev of the 4th Quartile Huff Distribution for Indiana

Figure 6.4.4 - The Average Huff Curves for Indiana

10% Huff Curve Ordinates

%StormTime	1st-Quartile		2nd-Quartile		3rd-Quartile		4th-Quartile	
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	45.76	1.49	17.20	1.53	18.01	1.70	24.83	1.90
20	66.36	2.87	26.21	0.66	25.75	1.03	33.35	0.88
30	76.52	2.86	45.86	1.57	32.36	1.17	38.26	1.19
40	82.05	2.63	70.94	1.75	39.15	1.00	43.44	1.21
50	85.46	2.36	85.17	1.26	48.43	1.11	48.85	0.95
60	88.01	2.09	90.11	1.03	70.52	1.81	53.47	1.17
70	90.32	1.93	92.85	0.93	86.13	1.18	59.45	1.04
80	92.75	1.77	95.12	0.86	93.73	0.99	73.24	0.89
90	95.76	1.27	97.28	0.61	96.92	0.69	91.29	0.98
100	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00

20% Huff Curve Ordinates

%StormTime	1st-Quartile		2nd-Quartile		3rd-Quartile		4th-Quartile	
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	36.01	1.17	13.40	1.11	13.92	1.45	19.60	1.68
20	55.44	3.05	23.02	0.66	21.96	1.08	28.76	1.52
30	67.85	2.67	39.76	1.08	28.10	1.06	33.72	0.70
40	74.40	2.84	62.54	1.67	34.58	0.89	38.55	1.21
50	78.84	2.69	79.02	1.27	44.20	1.01	43.48	1.16
60	82.48	2.50	85.75	1.09	63.77	1.31	49.02	0.95
70	85.77	2.42	89.67	1.05	81.09	1.17	54.66	1.38
80	89.20	2.26	92.96	1.04	91.02	1.05	68.71	0.98
90	93.50	1.73	96.05	0.78	95.58	0.84	87.63	1.06
100	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00

30% Huff Curve Ordinates

%StormTime	1st-Quartile		2nd-Quartile		3rd-Quartile		4th-Quartile	
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	30.75	1.05	11.33	0.93	11.63	1.25	16.48	1.57
20	50.69	1.40	20.42	0.42	19.24	0.97	24.84	0.99
30	61.36	3.04	35.95	0.80	25.11	0.66	30.97	1.08
40	68.64	2.68	57.13	1.36	31.35	0.93	34.62	1.00
50	73.34	3.11	74.33	1.25	41.21	0.95	39.69	1.16
60	77.82	2.72	82.27	1.09	59.30	1.21	44.60	1.30
70	81.72	2.78	87.01	1.00	77.32	1.26	50.68	0.95
80	85.89	2.70	91.02	1.17	88.72	1.10	65.24	1.05
90	91.44	2.07	94.95	0.90	94.43	0.87	84.85	1.07
100	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00

Table 6.4.1 - Mean & Stdev of Huff Distribution for Indiana

40% Huff Curve Ordinates

%StormTime	1st-Quartile		2nd-Quartile		3rd-Quartile		4th-Quartile	
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	26.30	1.01	9.82	0.83	9.88	1.08	14.05	1.45
20	47.86	1.20	18.79	0.70	16.81	1.07	21.96	1.34
30	55.26	3.38	32.89	0.80	22.49	0.91	27.17	1.12
40	63.85	3.02	52.91	1.31	28.20	1.12	32.47	0.78
50	68.77	2.70	70.26	1.35	38.37	0.99	35.90	1.50
60	73.41	3.18	79.19	0.84	55.54	1.15	40.47	1.35
70	77.83	3.00	84.53	1.04	74.06	1.12	47.41	1.57
80	82.60	3.12	89.12	1.18	86.55	1.05	61.32	1.25
90	89.36	2.42	93.86	0.98	93.32	0.90	82.29	1.17
100	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00

50% Huff Curve Ordinates

%StormTime	1st-Quartile		2nd-Quartile		3rd-Quartile		4th-Quartile	
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	23.16	1.11	8.59	0.84	8.39	1.01	11.93	1.38
20	41.94	1.13	16.71	0.58	14.73	1.16	19.24	1.15
30	51.52	2.32	29.89	0.76	19.87	0.81	24.41	0.87
40	58.21	3.56	49.02	1.15	25.42	0.87	28.70	1.12
50	65.26	2.72	66.34	1.32	35.03	1.23	33.17	0.81
60	69.25	2.95	76.03	0.81	52.05	1.15	36.33	1.65
70	73.97	3.43	82.13	1.06	70.98	1.04	42.89	1.55
80	79.23	3.51	87.19	1.14	84.44	1.04	57.38	1.45
90	87.07	2.84	92.75	1.00	92.11	0.94	79.49	1.20
100	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00

60% Huff Curve Ordinates

%StormTime	1st-Quartile		2nd-Quartile		3rd-Quartile		4th-Quartile	
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	19.92	0.82	7.48	0.85	7.16	0.94	10.10	1.20
20	38.56	0.90	14.88	0.78	12.75	1.13	16.61	1.35
30	50.34	0.89	27.15	0.70	17.49	1.06	21.21	1.25
40	53.40	3.36	45.48	1.00	22.62	1.20	25.16	0.90
50	59.82	3.75	62.77	1.20	31.34	1.48	29.50	1.30
60	66.33	2.54	73.34	0.96	48.31	1.39	33.16	0.93
70	69.93	3.44	79.72	0.80	67.73	1.11	38.57	1.64
80	75.64	3.92	85.21	1.17	82.27	1.10	52.46	1.58
90	84.40	3.39	91.52	1.04	90.80	0.99	76.02	1.40
100	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00

Table 6.4.1 - Mean & Stdev of Huff Distribution for Indiana (contd.)

70% Huff Curve Ordinates

%StormTime	1st-Quartile		2nd-Quartile		3rd-Quartile		4th-Quartile	
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	17.63	1.16	6.32	0.83	5.95	0.89	8.39	1.15
20	34.21	0.73	12.81	0.80	10.66	1.13	13.89	1.33
30	47.38	1.08	24.19	0.72	14.89	1.04	17.92	1.26
40	51.02	1.95	41.98	1.05	19.37	1.12	21.50	1.29
50	54.20	4.08	59.71	0.87	26.94	1.48	25.05	1.11
60	61.01	3.85	70.11	1.01	43.76	1.46	28.71	1.48
70	66.85	3.16	76.85	0.90	64.44	1.09	34.02	1.25
80	71.14	4.56	83.05	1.11	80.07	0.95	47.39	1.85
90	81.34	3.62	89.98	1.11	89.27	1.08	71.71	1.67
100	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00

80% Huff Curve Ordinates

%StormTime	1st-Quartile		2nd-Quartile		3rd-Quartile		4th-Quartile	
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	14.71	0.90	5.10	0.78	4.75	0.84	6.62	1.07
20	31.57	0.61	10.47	0.90	8.49	1.05	10.99	1.21
30	41.77	1.53	20.62	0.84	11.90	0.96	14.22	1.15
40	49.60	0.80	37.67	1.13	15.63	1.14	17.17	1.22
50	51.33	2.56	56.35	1.07	22.17	1.49	20.20	1.47
60	54.36	4.41	66.48	0.99	37.94	1.84	23.27	1.62
70	59.91	5.38	74.10	0.80	60.49	1.23	28.76	1.81
80	66.13	4.93	80.47	0.84	77.26	1.08	40.15	2.18
90	77.16	4.31	87.93	1.30	87.25	1.24	65.68	1.81
100	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00

90% Huff Curve Ordinates

%StormTime	1st-Quartile		2nd-Quartile		3rd-Quartile		4th-Quartile	
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	11.60	1.00	3.66	0.67	3.36	0.72	4.63	0.88
20	26.78	0.59	7.41	0.82	6.01	0.99	7.65	1.04
30	36.06	1.84	15.59	1.00	8.32	1.01	9.83	1.11
40	42.58	2.31	31.71	1.46	10.94	1.17	11.88	1.18
50	49.94	0.82	51.70	0.88	15.53	1.61	13.98	1.31
60	51.19	2.47	61.96	1.05	28.83	2.64	16.48	1.54
70	52.78	4.45	69.43	1.03	54.14	1.66	20.95	2.01
80	56.37	6.48	76.50	1.04	73.83	0.83	30.83	2.24
90	70.13	5.04	84.25	1.65	83.70	1.71	54.64	2.95
100	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00

Table 6.4.1 - Mean & Stdev of Huff Distribution for Indiana (contd.)

Figure 6.4.5 - The Fitted Huff Curves for Indiana

10% Fitted Huff Curve Coefficients				
Coefficients	1st-Quartile	2nd-Quartile	3rd-Quartile	4th-Quartile
H ₁	4.089E+00	9.827E-01	1.094E+00	2.090E+00
H ₂	2.966E-01	3.430E-01	3.481E-01	2.288E-01
H ₃	-4.637E-02	-5.010E-02	-5.409E-02	-3.578E-02
H ₄	2.663E-03	3.114E-03	3.705E-03	2.136E-03
H ₅	-8.676E-05	-1.024E-04	-1.430E-04	-7.213E-05
H ₆	1.751E-06	1.975E-06	3.338E-06	1.520E-06
H ₇	-2.231E-08	-2.317E-08	-4.784E-08	-2.045E-08
H ₈	1.745E-10	1.633E-10	4.109E-10	1.708E-10
H ₉	-7.651E-13	-6.360E-13	-1.941E-12	-8.067E-13
H ₁₀	1.441E-15	1.053E-15	3.873E-15	1.642E-15

20% Fitted Huff Curve Coefficients				
Coefficients	1st-Quartile	2nd-Quartile	3rd-Quartile	4th-Quartile
H ₁	3.328E+00	1.031E+00	9.766E-01	1.747E+00
H ₂	1.840E-01	1.388E-01	1.987E-01	1.287E-01
H ₃	-3.007E-02	-1.910E-02	-3.036E-02	-2.025E-02
H ₄	1.794E-03	1.045E-03	2.061E-03	1.200E-03
H ₅	-6.097E-05	-2.722E-05	-7.942E-05	-4.127E-05
H ₆	1.280E-06	3.478E-07	1.853E-06	9.046E-07
H ₇	-1.685E-08	-1.597E-09	-2.649E-08	-1.279E-08
H ₈	1.353E-10	-9.158E-12	2.263E-10	1.126E-10
H ₉	-6.061E-13	1.277E-13	-1.060E-12	-5.581E-13
H ₁₀	1.161E-15	-3.883E-16	2.092E-15	1.184E-15

30% Fitted Huff Curve Coefficients				
Coefficients	1st-Quartile	2nd-Quartile	3rd-Quartile	4th-Quartile
H ₁	2.907E+00	9.897E-01	9.041E-01	1.639E+00
H ₂	9.569E-02	6.703E-02	1.238E-01	5.007E-02
H ₃	-1.378E-02	-8.973E-03	-1.885E-02	-1.041E-02
H ₄	6.629E-04	4.176E-04	1.269E-03	6.645E-04
H ₅	-1.853E-05	-6.036E-06	-4.876E-05	-2.461E-05
H ₆	3.286E-07	-7.613E-08	1.135E-06	5.805E-07
H ₇	-3.729E-09	3.587E-09	-1.613E-08	-8.755E-09
H ₈	2.613E-11	-4.728E-11	1.365E-10	8.123E-11
H ₉	-1.025E-13	2.828E-13	-6.309E-13	-4.196E-13
H ₁₀	1.712E-16	-6.565E-16	1.227E-15	9.193E-16

Table 6.4.2 - Regression Coefficients of Huff Curves

40% Fitted Huff Curve Coefficients

Coefficients	1st-Quartile	2nd-Quartile	3rd-Quartile	4th-Quartile
H ₁	2.559E+00	9.309E-01	8.584E-01	1.095E+00
H ₂	-1.054E-02	1.972E-02	6.815E-02	1.442E-01
H ₃	7.589E-03	-1.611E-03	-1.086E-02	-2.084E-02
H ₄	-9.451E-04	-6.448E-05	7.418E-04	1.276E-03
H ₅	4.556E-05	1.085E-05	-2.895E-05	-4.480E-05
H ₆	-1.174E-06	-4.244E-07	6.825E-07	9.748E-07
H ₇	1.773E-08	7.972E-09	-9.743E-09	-1.339E-08
H ₈	-1.575E-10	-8.051E-11	8.207E-11	1.132E-10
H ₉	7.632E-13	4.225E-13	-3.749E-13	-5.365E-13
H ₁₀	-1.559E-15	-9.072E-16	7.163E-16	1.090E-15

50% Fitted Huff Curve Coefficients

Coefficients	1st-Quartile	2nd-Quartile	3rd-Quartile	4th-Quartile
H ₁	2.574E+00	8.205E-01	7.107E-01	1.169E+00
H ₂	-1.097E-01	1.383E-02	6.146E-02	2.691E-02
H ₃	1.729E-02	-8.576E-04	-9.400E-03	-4.540E-03
H ₄	-1.376E-03	-9.354E-05	6.389E-04	2.166E-04
H ₅	5.615E-05	1.100E-05	-2.487E-05	-5.838E-06
H ₆	-1.324E-06	-4.071E-07	5.826E-07	1.071E-07
H ₇	1.887E-08	7.473E-09	-8.230E-09	-1.459E-09
H ₈	-1.607E-10	-7.450E-11	6.829E-11	1.407E-11
H ₉	7.541E-13	3.876E-13	-3.060E-13	-8.100E-14
H ₁₀	-1.501E-15	-8.277E-16	5.714E-16	2.002E-16

60% Fitted Huff Curve Coefficients

Coefficients	1st-Quartile	2nd-Quartile	3rd-Quartile	4th-Quartile
H ₁	2.549E+00	7.349E-01	5.688E-01	9.977E-01
H ₂	-2.050E-01	3.115E-03	6.781E-02	2.031E-02
H ₃	2.612E-02	5.253E-04	-1.027E-02	-3.756E-03
H ₄	-1.587E-03	-1.612E-04	7.086E-04	2.112E-04
H ₅	5.115E-05	1.241E-05	-2.767E-05	-7.481E-06
H ₆	-9.609E-07	-4.123E-07	6.449E-07	1.846E-07
H ₇	1.087E-08	7.194E-09	-9.027E-09	-3.061E-09
H ₈	-7.280E-11	-6.949E-11	7.415E-11	3.151E-11
H ₉	2.641E-13	3.536E-13	-3.289E-13	-1.784E-13
H ₁₀	-3.964E-16	-7.421E-16	6.078E-16	4.203E-16

Table 6.4.2 - Regression Coefficients of Huff Curves (contd.)

70% Fitted Huff Curve Coefficients

Coefficients	1st-Quartile	2nd-Quartile	3rd-Quartile	4th-Quartile
H ₁	1.778E+00	7.167E-01	4.029E-01	7.945E-01
H ₂	1.956E-02	-3.806E-02	8.429E-02	3.062E-02
H ₃	-6.380E-03	6.518E-03	-1.246E-02	-5.075E-03
H ₄	6.791E-04	-5.787E-04	8.558E-04	3.126E-04
H ₅	-3.553E-05	2.870E-05	-3.289E-05	-1.152E-05
H ₆	9.995E-07	-7.922E-07	7.480E-07	2.746E-07
H ₇	-1.607E-08	1.261E-08	-1.018E-08	-4.218E-09
H ₈	1.485E-10	-1.159E-10	8.104E-11	3.990E-11
H ₉	-7.348E-13	5.723E-13	-3.472E-13	-2.093E-13
H ₁₀	1.511E-15	-1.179E-15	6.168E-16	4.630E-16

80% Fitted Huff Curve Coefficients

Coefficients	1st-Quartile	2nd-Quartile	3rd-Quartile	4th-Quartile
H ₁	1.404E+00	7.074E-01	2.611E-01	5.542E-01
H ₂	-1.172E-02	-8.664E-02	8.753E-02	5.073E-02
H ₃	5.646E-03	1.377E-02	-1.221E-02	-7.449E-03
H ₄	-5.126E-04	-1.100E-03	7.942E-04	4.676E-04
H ₅	2.214E-05	4.953E-05	-2.860E-05	-1.706E-05
H ₆	-5.659E-07	-1.287E-06	6.010E-07	3.879E-07
H ₇	8.929E-09	1.979E-08	-7.392E-09	-5.553E-09
H ₈	-8.484E-11	-1.782E-10	5.135E-11	4.845E-11
H ₉	4.432E-13	8.706E-13	-1.807E-13	-2.341E-13
H ₁₀	-9.755E-16	-1.784E-15	2.342E-16	4.784E-16

90% Fitted Huff Curve Coefficients

Coefficients	1st-Quartile	2nd-Quartile	3rd-Quartile	4th-Quartile
H ₁	1.739E+00	7.973E-01	2.251E-01	5.553E-01
H ₂	-2.678E-01	-1.810E-01	3.716E-02	-3.061E-02
H ₃	4.069E-02	2.728E-02	-3.790E-03	4.155E-03
H ₄	-2.804E-03	-2.050E-03	1.217E-04	-3.377E-04
H ₅	1.059E-04	8.672E-05	1.458E-06	1.501E-05
H ₆	-2.395E-06	-2.153E-06	-1.981E-07	-3.908E-07
H ₇	3.330E-08	3.207E-08	5.453E-09	6.161E-09
H ₈	-2.795E-10	-2.827E-10	-7.071E-11	-5.794E-11
H ₉	1.300E-12	1.360E-12	4.491E-13	2.995E-13
H ₁₀	-2.577E-15	-2.756E-15	-1.125E-15	-6.547E-16

Table 6.4.2 - Regression Coefficients of Huff Curves (contd.)

VII. Conclusions

The following conclusions are presented on the basis of this study.

1. For selection of probability distributions for rainfall data, EV(1), GEV, P(3), LP(3), and Pareto distributions are tested. GEV is found suitable for the entire state of Indiana.
2. For the generalized IDF formula, the parameters estimated by Indiana rainfall data exhibit 2nd order polynomial trend. The parameters of the 2nd order polynomial form are presented. The result of split sample test also supports the consistency of the method.
3. The ratio R_T in Chen's method changes significantly depending on T . Therefore it is better to use different ratio R_T for different return periods. Maps of R_T of different return periods are provided for Indiana.
4. The assumption that x_t in Chen's method does not change significantly depending on duration t , is acceptable for Indiana data. Hence, x_1 can be used to represent all x_t .
5. For generalized IDF formula, using the ratio R_T from the map provided, and then using the 2nd order polynomial to calculate the coefficients is the recommended method for use in Indiana.
6. For Indiana data, NWS rainfall estimate matches GEV estimate best, and Huff-Angel estimate worst. The latest NWS estimate result is better than the DNR estimate which is adopted from TP-40 and Hydro-35.
7. Investigation of ratios under several different return periods shows that ratio approach used to develop Huff-Angel estimate is not suitable, especially for high return periods.

8. It is found that Huff curves from different stations in Indiana are quite similar. For practical use, the average Huff curve of all stations in Indiana can be used as the representative Huff curve of Indiana.
9. To facilitate the computations, regression models of Huff curves are fitted and presented.
10. It is shown that rainfall in Indiana is quite homogeneous. Hence, a single probability density function and temporal rainfall distribution and a single set of Huff curves can be used to describe the rainfall properties over the state.

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