LITERATURE REVIEW

History

In 1888, the U.S. Signal Service installed the first automatic rain gage used to record intensive precipitation for short periods (Yarnell, 1935). Using the records from this and the approximately 200 other automatic recording rain gages added throughout the United States by the Weather Bureau, David L. Yarnell, the senior drainage engineer for the U.S. Department of Agriculture developed intensity-frequency diagrams for some durations and all stations from all records through 1933. The published reports of the Weather Bureau showed the accumulated amounts of precipitation at 5-minute intervals which equaled or exceeded the volumes indicated in Table 2.1.

Table 2.1. Minimum Accumulated Volumes of Precipitation in 5-minute Intervals Reported by the U.S. Weather Bureau.

Time Period (Minutes)	**Minimum Volume (Inches)**	**Intensity (Inches/Hour) ***
5	0.25	3.00
10	0.30	1.80
15	0.35	1.40
.	.	.
.	.	.
.	.	.
60	0.80	0.80
120	1.40	0.70

* calculated from original data of columns one and two

Yarnell's research found that in some cases the actual 5-minute precipitation during any storm commonly exceeded the Weather Bureau's published data by 8 to 10 percent when determined from the particular interval of greatest downfall rather than from the series of regular intervals. Similar discrepancies were also found for the 1- and 2-hour published records. It was determined that the probable cause of the discrepancies between the actual maximum precipitation and the published data was because the rainfall for low rates at the beginning and the end of the storms were not included in the Weather Bureau's report. Using the actual observed data through 1933, Yarnell plotted linear intensity-frequency diagrams for all stations using the 5-, 10-, 15-, 30-, 60-, 100-, and 120-minute durations. From these diagrams the maximum intensities were determined for the 5-minute to 2-hour storms. Graphic interpolation was used for the 4-hour, 8-hour, and 16-hour storms. The 10-minute to 2-hour and 24-hour data obtained from these diagrams were plotted on logarithmic paper. Using points of equal frequency, the 4-, 8-, and 16-hour durations were obtained by smooth curves being drawn from the 2-hour to 24-hour durations. Precipitation intensity for different durations and return periods were then plotted on an outline map of the United States. Isohyetals, lines of equal precipitation as inches per hour, were then drawn across the map. (Yarnell, 1935)

In 1955, a cooperative study was published in Technical Paper No. 25 (TP-25) by the U.S. Weather Bureau and the Soil Conservation Service presenting rainfall intensity-duration curves for durations of 5- minutes to 24-hours, and return periods of 2-, 5-, 10-, 25-, 50-, and 100-years for the same rainfall stations used in Yarnell's study. The published curves for the state of Florida included Apalachicola, Jacksonville, Key West, Miami, Pensacola, Sand Key, and Tampa. When rainfall intensity-frequency data were needed at any location an appreciable distance from a station with a published curve, the local short-record rainfall data needed to be related to the corresponding nearby longer-record rainfall stations. The appropriate intensity-duration curve would then be chosen based on similarities of rainfall data.

Six years later in 1961, David M. Hershfield prepared for the U.S. Weather Bureau the Rainfall Frequency Atlas of the United States which is known as Technical Paper No. 40 (TP-40). Rainfall volumes and intensities for durations from 30 minutes to 24 hours and for return periods of 1 to 100 years were reported in TP-40. The same 200 rainfall stations originally used by Yarnell were used in TP-40 as long-record data. For short return periods such as the 2-year period, about 5,000 stations located throughout the United States provided the necessary rainfall data. For accuracy of statistical analysis, no record of less than five years was used to estimate the 2-year record (Hershfield, 1961). The method used for analysis in Hershfield's study was the partial-duration series. To obtain the partial series data, the rainfall records were first analyzed to obtain the maximum annual intensity and then transformed to partial-duration data. The factors used in the transformation were determined using the mean values of both the annual and partial series analyses of the 1-, 6-, and 24-hour durations. These values were comparable to the 2.3-year (average) return period intensities. Based on these intensities, Table 2.2 contains the values used for the transformation of the partial-duration series data to annual series data.

Table 2.2. Factors Used in TP-40 to Convert Partial Series Data to Annual Series Data.

Return Period (years)	Conversion Factor
2	0.88
5	0.96
10	0.99

Theoretical analysis using the Gumbel distribution of the annual series data was used for the 20-year and longer return periods. The empirical method of analysis was used for the return periods of 10 years or less and was based on freehand curves drawn through plottings of partial-duration series data. Forty-nine (49) isopluvial (lines of equal rainfall) maps of the United States were developed for combinations of duration and return periods.

In 1977, the National Weather Service (NWS), Soil Conservation Service (SCS), and the U.S. Department of Agriculture, in a combined effort to better define the shorter duration rainfall values, developed HYDRO-35. The intensities for durations of less than one hour as reported in TP-40 used nation-wide ratios of shorter duration values to one-hour values. The intensities were found to vary with return period, and were shown to have a definite geographic pattern. HYDRO-35 reported the 5-, 15-, and 60-minute durations for the 2-, and 100-year return periods for the portion of the United States from North Dakota to Texas and eastward derived from hourly precipitation data collected by National Oceanic and Atmospheric Administration (NOAA). Nomograms and equations were also reported for use in interpolating intensities for intradurations and intrareturn periods.

The data analysis for HYDRO-35 consisted of computer processing of data tapes to extract the maximum hourly recorded rainfall per month for each station. From these maximum hourly records, maximum yearly rainfall data were recorded for the annual series frequency analysis. A requirement of HYDRO-35 was that the results be expressed in terms of partial-duration frequencies (NOAA, 1977). The annual series data were multiplied by conversion factors to obtain the equivalent partial-duration series values. These conversion factors are the reciprocals of the factors used in TP-40 and were used to avoid laborious processing of partial-duration data. Table 2.3 contains the factors used in HYDRO-35 for the conversion.

Table 2.3. Factors Used in HYDRO-35 to Convert Annual Series Data to Partial Series Data.

Return Period (years)	**Conversion Factor**
2	1.13
5	1.04
10	1.01
25	1.00
50	1.00
100	1.00

The frequency distributions studied for use in HYDRO-35 were the Pearson Type III, the Log Pearson Type III, and the Gumbel Type I (referred to as the Fisher-Tippett Type I). The predictions from the 1-, 6-, and 24-hour durations were compared to determine the percent of observations that equaled or exceeded calculated values. The analysis showed no significant differences in results obtained. The Gumbel Type I

Method of Moments frequency distribution was then chosen for use in HYDRO-35 since it was the method of choice in previous studies.

TP-40 used both the 60-minute and 24-hour duration while HYDRO-35 used the 60-minute duration as a basis for the development of IDF maps. It was further determined that the 2-year return period for both studies produced similar results and therefore would be used in conjunction with the 60-minute duration as a base map for HYDRO-35. For the Florida peninsula, the intensities presented in TP-40 and HYDRO-35 were similar. However, the HYDRO-35 study considered the intensity of thunderstorms created by solar heating of land and reported higher values for rainfall intensity for the interior portion of the peninsula.

In 1979, the Florida Department of Transportation developed rainfall intensity-duration-frequency curves for the state using the most current rainfall data. Using the procedures from both HYDRO-35 and TP-40, IDF curves were developed for each of the 68 counties of Florida. To establish zones of homogeneous rainfall, FDOT used the 2-year and 100-year return periods as their base maps. To be conservative, where wide variations in rainfall were found within county borders of areas expected to be developed, the greatest values were used for that county. After determining the homogeneity of rainfall across the state for the 2-, and 100-year maps, FDOT constructed maps for the 10-, 15-, and 30-minute intensities, and the 1-, 2-, 3-, 6-, 12-, and 24-hour intensities. Noting that the intensity curves created from TP-40 did not match up with curves from the data HYDRO-35, the FDOT hand fit the 68 maps developed for the 2-year and 100-year return periods. Using the 6 zones previously developed for the state as a basis for delineation, the FDOT determined that 11 zones of homogeneous rainfall were needed to provide accurate coverage of the state. Within each of the 11 zones, one county was selected as a representative for the zone. Typically, the county with the most data available was chosen as the representative. Using these rainfall data for the selected counties, the final IDF curves were developed for each of the 11 zones containing the 2-, 3-, 5-, 10-, 25-, 50-, and 100-year return period intervals.

Statistical Analysis

With the possibility of including additional rainfall data using computer programs, a statistical analysis is possible for many locations. The output of a hydrologic system is treated as stochastic, space-independent, and time-independent when there is no correlation between adjacent observations. For hydrologic data, such as precipitation, or extreme events, such as floods or droughts, this type of treatment for analysis is applicable. Random variables are statistically described by a probability distribution. The probability of an event is the chance that it will occur based on an observation of the random variable. The larger the sample size of random variables the better the estimate of the probability of the event. To determine the probability of events occurring, probability distribution functions are fit to the data to determine the appropriate function to use for estimation of the events. There are two methods for fitting distributions to data: *method of moments* and *method of maximum likelihood*. Karl Pearson developed the method of moments in 1902. Pearson's method of moments selects probability function parameters such that the moments are equal to those of the sample data. The first moment for each observation is the sample mean, the second is the variance, and the third is the coefficient of skewness. R.A. Fisher developed the method of maximum likelihood in 1922. Fisher's method for determining the parameter of a probability distribution is finding the parameter values which maximizes the likelihood of occurrence. Although the method of maximum likelihood is considered the most theoretically correct for fitting probability distributions, it can be computationally unstable. Therefore, the method of moments has been found to be more suitable for hydrologic analysis.

Frequency analyses of hydrologic data use probability distributions to relate the magnitude of extreme events to their frequency of occurrence. The distribution functions most often used when estimating hydrologic events were: *Normal, 2 Parameter Log Normal, 3 Parameter Log Normal, Pearson Type III, Log Pearson Type III,* and *Gumbel Type I*. Annual precipitation events tend to follow the normal distribution, and distribution varies over a continuous range and is symmetric about the mean but allows negative values. However, hydrologic variables tend to be skewed and all are non-negative. The log normal distribution eliminates the problem of non-negative variables as the data are greater than zero, permits the skewness of the data, and does require the data to be symmetric about the logarithm of the mean. The Pearson Type III methods transform the mean, standard deviation, and the coefficient of skewness into the three parameters of the distribution function. When the data are greatly skewed, the log transformation of the Pearson Type III is used to reduce the skewness. Next, the Gumbel Type I distribution, also known as the Extreme Value Type I distribution, is a two-parameter distribution. One parameter is the most probable value of the distribution and the second is a measure of dispersion. Extreme value distributions have been widely used in hydrology (Chow et al., 1988). Analyzing data for the largest or smallest observations from sets of data became the basis for using the Gumbel (Extreme Value) Type I distribution. The Gumbel is also readily solved by hand calculations. In the early 1980s, a comparison of the various distribution functions available for analysis of rainfall frequencies showed that the Log Pearson Type III distribution became method of choice. As a result, in 1981 the U.S. Water Resources Council (now called Interagency Advisory Committee on Water Data) recommended the Log Pearson Type III distribution be used in an effort to promote consistency for flood flow analysis. An independent study showed that this distribution was the most appropriate method of estimation of rainfall data (Naghavi et al., 1991).

During the most recent ten years, regions of the United States have been studing the longer records of precipitation data available using better statistical methods. The result of these studies provide new recommendations for distribution analysis. As its primary reference for statistical method, the National Weather Service is using the 1997 Hosking and Wallis regional frequency analysis which uses the method of L-moments (Hosking and Wallis, 1997). The method of L-moments, accepted by most as the state of practice for determining the appropriate probability distribution function describing rainfall frequency.

A study performed in Montana, as reported in the "Regional Analysis of Annual Precipitation Maxima in Montana" (Parrett, 1997), used L-moment based statistics to examine the goodness-of-fit test. Analyzing 459 gauging stations, Parrett chose as the best distribution the generalized extreme-value (GEV) for all durations.

In 1998, a study performed in Texas, "Regionalization of Precipitation Maxima for Texas" (Asquith, 1998), determined that the annual maxima for the 12-hour and less durations were best fit using the generalized logistic distribution (GLO). However, Asquith found that the generalized extreme value (GEV) distribution best fit his longer durations.

The University of Alabama (Cole, 1998) used L-moment ratio diagrams to determine the best probability distribution for modeling the annual rainfall extremes in Alabama. Analyzed distributions included the generalized Pareto (GPA), generalized extreme-value (GEV), generalized logistic (GLO), lognormal (LN3), and the Pearson Type III (PE3). Based on the ratio diagrams, Durans and Cole chose the generalized extreme-value (GEV) distribution for all durations.

Spatial Variability

Rainfall values vary throughout the state. Storm duration's, volumes, and rainfall intensities vary. The prediction of expected rainfall values at specific locations are necessary in the design of FDOT drainage systems and other engineering projects. Determination of the expected rainfall for a particular storm duration and design frequency at a location where there is no recording station requires spatial analysis of the available rainfall values from the surrounding area. The development of isohyets for use in estimating rainfall is one of the commonly used methods of spatial analysis.

In 1935, David Yarnell plotted isohyetals for desired durations and frequencies (return periods) using rainfall intensities selected from the intensity-frequency diagrams that he developed. The plotted values were weighted using best judgment with consideration to the character and length of the records from the rainfall stations. Technical Paper No. 40 (TP-40) developed by the U.S. Weather Bureau in 1961 generated isopluvial (lines of equal rainfall) maps for the 2-year 1-hour, 2-year 24-hour, 100-year 1-hour, and 100-year 24-hour return period and duration combinations. These four maps were then used in the construction of 45 additional return period and duration maps. Rainfall values were then computed for 3500 grid points throughout the United States using data read from each of the four maps for each grid point. Isolines were then positioned on the additional 45 maps by interpolation. TP-40 used this spatial methodology to maintain internal consistency of the series of maps.

HYDRO-35, developed in 1977 by the National Oceanic and Atmospheric Administration (NOAA) and the National Weather Service, constructed six isopluvial maps using the intensities developed from the distribution analysis. These six maps were for storm durations of 5-, 15-, and 60-minutes for each return period of 2-, and 100-years. Computerized space-averaging techniques used by the National Meteorological Center analyzed grid points spaced at each half degree of longitude and latitude. The smoothing program utilized linear and exponential weighting functions to progressively adjust the grid point estimates. Each of the six isopluvial maps were then reconstructed incorporating the values obtained from the smoothing program for the half-degree latitude-longitude grid system.

In 1979, the Florida Department of Transportation (FDOT) modified the intensity-duration-frequency curves for the state using the procedures followed in TP-40 and HYDRO-35. The FDOT used the 10-, 15-, 30-, and 60-minute data from HYDRO-35, and the 1-, 2-, 3-, 6-, 12-, and 24-hour data from TP-40 to develop curves for the 2-year and the 100-year return periods. Noting that the curves from TP-40 and HYDRO-35 did not match up, the curves were then smoothed between the one and three hour durations. Determining that the two types of rainfall in the state made the development of isopluvials impossible, the FDOT abandoned this concept. Using the previous 6 zone delineation as a guideline, the FDOT developed the currently used 11 IDF curves.

The Alabama Rainfall Atlas, revised in 2002 by Duran and Brown, provides databases of the three parameters of the GEV distribution rather than rainfall depths (Duran and Brown, 2002). A developed spatial smoothing algorithm, a hybrid of two methods, is used for a rainfall depth at an ungauged site. This smoothing, rather than interpolation algorithm regionalizes rainfall parameter estimates. It incorporates information at surrounding gauging sites and is similar to the “region of influence” approach to regionalization used by Hosking and Wallis, 1997.

References:

Asquith, William H. "Regionalization of Precipitation Maxima for Texas." U. S. Geological Survey, Water Resources Division, 1998.

Chow, Ven Te, David R. Maidment, and Larry W. Mays. Applied Hydrology. McGraw-Hill, New York, 1988.

Cole, A.. Statistical Analyses to Support the Development of an Internet-Based Alabama Rainfall Atlas, M.S. thesis, Department of Civil and Environmental Engineering, University of Alabama, Tuscaloosa, Alabama, 1998.

Durrans, S. R. and Borwn, P. A. "Development of an Internet-based rainfall atlas for Alabama. University of Alabama, Tuscaloosa, Alabama, 2002.

Hershfield, David M. "Estimating the Probable Maximum Precipitation". Journal of the Hydraulics Division ASCE Proceedings, September 1961, pages 99 - 116.

Hershfield, David M. "Rainfall Frequency Atlas of the United States". U.S. Department of Commerce, Technical Paper No. 40, Washington, D.C., October 1986.

Hosking, J.R.M. and Wallis, J.R. "Regional Frequency Analysis: An Approach Based on L-moments." Cambridge University Press, 1997.

Naghavi, Babak, Vijay P. Singh, Fang Xin Yu. "LADOTD 24-Hour Rainfall Frequency Maps and I-D-F- Curves (Summary Report)". Louisiana State University, Baton Rouge, LA., August 1991.

National Oceanic and Atmospheric Administration. "Five- to 60-Minute Precipitation Frequency for the Eastern and Central United States". Technical Memorandum NWS HYDRO-35, Silver Spring, MD., June 1977.

Parrett, Charles. "Regional Analysis of Annual Precipitation Maxima in Montana, Water-Resources Investigations Report 97-4004." U. S. Geological Survey, Helena, Montana, 1997.

Technical Paper No. 29. "Rainfall Intensity-Frequency Regime, Part 2-Southeastern United States". U.S. Department of Commerce, Washington, D. C., March 1958.

U.S. Weather Bureau, and Soil Conservation Service. "Rainfall Intensity-Duration-Frequency Curves". U.S. Department of Agriculture, Technical Paper No. 25, Washington, D.C., December 1955.

Yarnell, David L. "Rainfall Intensity-Frequency Data". United States Department of Agriculture, Miscellaneous Publication No. 204, Washington, D.C., August 1935.