EXECUTIVE SUMMARY

Background

Due to the perceived occurrence of high-intensity storms more frequently than expected, the Michigan Department of Transportation (MDOT) has deemed it necessary to update the regional rainfall intensity-duration-frequency (IDF) estimates for the State. Recently, a nine-state study has shown that stations in the Midwest, including those in Michigan, have measured an unexpected number of heavy rainfall events in recent years (Angel and Huff, 1997). For Michigan, it was found that the 24-hour, 100-year value was exceeded 71 times, while only 21 exceedances were expected. In general, it is recommended that rainfall frequency studies be updated on a regular basis for maximum reliability.

Objectives

The overall objective of this study is to revise Michigan's rainfall IDF estimates by: 1) obtaining and screening the most up-to-date gaged rainfall data; 2) delineating homogeneous regions for a regional frequency analysis; 3) fitting an appropriate 3-parameter probability distribution to the observed data; 4) estimating the distribution parameters; 5) spatially interpolating a site-specific scale factor to account for regional variability; and 6) presenting revised IDF estimates in tabular and graphical forms. Additionally, the development of an interactive geographical information system (GIS) model for display and retrieval of site-specific rainfall IDF estimates is discussed. Rainfall intensity estimates are determined for each of eleven durations (5, 10, 15, 30, 60,

120, 180, 360, 720, 1080, and 1440 minutes) and six recurrence intervals (2, 5, 10, 25, 50 and 100 years).

Data Used

This study utilizes data from 76 hourly and 152 daily rainfall-recording stations throughout Michigan, along with 81 Southeast Michigan Council of Governments (SEMCOG) short duration rainfall-recording stations located in 5 counties in and around the Detroit area (see Figure 3.1). Annual maximum series (AMS) data, containing the largest value in each year, were compiled from hourly and daily data. (AMS data were not available for the SEMCOG recording stations.) Partial duration series (PDS) series data, containing a certain number of the largest values regardless of the year in which they were recorded, were compiled for all durations. In this study, each PDS series contains the 2*N* highest rainfall intensity values, where *N* is the number of years of record.

In the analysis, rainfall intensities for 5 to 30 minutes were based on the SEMCOG data, intensities for durations from 1 to 18 hours were derived from hourly records, and 24-hour were derived from daily records. SEMCOG recording stations have record lengths ranging from 16 to 38 years, with an average record length of 30 years (through 1999). The hourly recording stations have record lengths ranging from 18 to 49 years, with an average record of 41 years (through 1996). The daily recording stations have record lengths ranging from 21 to 117 years, with an average record of 63 years (through 1996).

Procedure

In contrast to a traditional at-site frequency analysis using the method of moments to estimate distribution parameters, this study applies a regional frequency analysis approach based on *L*-moments. In a regional frequency analysis, regional information is used to increase the reliability of rainfall IDF estimates at any particular site (Hosking and Wallis, 1997). One limitation is that the procedure assumes that sites from a homogeneous region have an identical frequency distribution apart from a site-specific scaling factor.

L-moments are defined as expectations of certain linear combinations of order statistics (Hosking, 1990). They are analogous to conventional moments with measures of location (mean), scale (standard deviation), and shape (skewness and kurtosis). Because *L*-moments are linear combinations of the ranked observations and do not involve squaring or cubing the observations as is done for the conventional method of moments estimators, they are generally more robust and less sensitive to outliers.

The procedure followed in this study is outlined below (Hosking and Wallis, 1997). The main steps are to screen the data, identify homogeneous regions, chose a frequency distribution, estimate the parameters of the chosen distribution, and compute quantile estimates.

(1) Screening the Data. The first step in any statistical investigation is to check that the data are suited for the analysis. Tests for gross outliers, inconsistencies, shifts, and trends are ways to check the appropriateness of the data. Additionally, Hosking and Wallis (1997) present a discordancy measure based on the *L*-moments of the sites' data. The discordancy measure is a single statistic based on the difference between

the L-moment ratios of a site and the average L-moment ratios of a group of similar sites. This statistic can also be used to identify erroneous data.

(2) Identifying Homogeneous Regions. The purpose of this step is to form groups of stations that satisfy the homogeneity condition, i.e., stations with frequency distributions that are identical apart from a station-specific scale factor. Stations can be grouped subjectively by site characteristics (i.e., latitude, longitude, elevation, and mean annual precipitation). For example, Schaefer (1990) defined homogeneous regions based on mean annual precipitation for a regional frequency analysis study of annual maximum precipitation in the State of Washington. Stations can also be grouped objectively using cluster analysis procedures. Cluster analysis is a multivariate statistical analysis procedure for partitioning a data set into groups. The procedure involves assigning a data vector to each site. Sites are then divided into groups based on the similarity of their data vectors. The data vectors can consist of site statistics, site characteristics, or some combination of both. Hosking and Wallis (1997) recommend basing the regionalization of sites on site characteristics alone.

(3) Choosing a Frequency Distribution. In regional frequency analysis, a single frequency distribution is fit to the data from several sites in a homogeneous region. Because the "true" distribution of rainfall is not known, a distribution must be chosen that not only provides a good fit to the data, but will also yield reliable and robust and quantile estimates for each site in the region. The candidate three-parameter distributions considered for quantile estimation in this study were the Generalized Logistic (GLO), the Generalized Extreme Value (GEV), the Lognormal (LN3), the Pearson Type III (PE3), and the Generalized Pareto (GPA). To aid in selection of an

appropriate distribution, Hosking and Wallis (1997) introduce another statistic called the *Z*-statistic. The *Z*-statistic is a goodness-of-fit measure for three-parameter distributions which measures how well the theoretical *L*-kurtosis of the fitted distribution matches the regional average *L*-kurtosis of the observed data.

(4) Parameter Estimation. To estimate a chosen distribution's parameters and obtain quantile estimates, the regional *L*-moment algorithm is used (Hosking and Wallis, 1997). This procedure involves fitting the chosen distribution using the method of *L*-moments; its parameters are estimated by equating the population *L*-moments of the distribution to the sample *L*-moments derived from the observed data. Next, sample *L*-moment ratios from each site in a homogeneous region are weighted according to record length and combined to give regional average *L*-moment ratios. Hosking and Wallis (1997) found that averaging *L*-moment ratios rather than the *L*-moments themselves yields more accurate quantile estimates in all cases examined. Next, the regional mean is set equal to 1, and regional quantile estimates are derived. Final quantile estimates are obtained by multiplying the regional quantile estimate by the index flood, which for this study is the at-site estimate of the mean.

(5) Determination of Rainfall IDF Estimates at Ungaged Sites. To obtain rainfall IDF estimates at ungaged sites, the regional quantile estimates derived from data at gaged sites within a region are interpolated to all ungaged sites in that region. Specifically, the index flood values (at-site means) are spatially interpolated over the State using geostatistical methods. This allows for rainfall IDF estimates for durations of 1, 2, 3, 6, 12, 18 and 24 hours to be determined for any location in

the State of Michigan. For durations of less than 1 hour, a procedure was devised to extrapolate the results obtained for the SEMCOG gages. The procedure assumes that the ratio of N-minute to 60-minute rainfall intensity is constant throughout the State.

Results

In screening the data, trend analyses were first conducted. Since analysis of the daily AMS data indicated a positive trend over time, it is recognized that some adjustment may be necessary to put greater weight on the more recent daily rainfall events. Little evidence of such trends was identified in the hourly AMS data, however; therefore no adjustments to results derived from hourly observations are deemed necessary. A negative trend over time was actually indicated in the short duration (10- and 30-minute) data, so no adjustments are recommended.

A temporal analysis of the daily PDS data revealed significant increases in the frequency of heavy rainfall in Michigan over a 70-year period (1927-96). In light of this, quantile estimates derived from the 1960-96 period were compared with those derived from the full period of record. No significant differences were found. As a result, no measures are recommended to account for the trend in the daily PDS data. To identify trends in the hourly PDS data, a quantile comparison was again conducted. For the 1- and 12-hour durations, quantile estimates derived from the 1974-96 period were compared with those derived from the full period of record. Significant differences were observed only at the 50- and 100-year recurrence intervals for the 12-hour duration. Taking into account sampling variability, and the fact that there were no significant differences in the daily and 1-hour quantile comparisons, these differences are not

accounted for in rainfall IDF estimation. For the 10- and 30-minute durations, the quantile estimates derived from the 1980-99 period were found to be lower than those from the full period of record. These differences are not accounted for in the rainfall IDF estimation as sampling variability over the relatively short period of record might account for this difference.

To identify homogeneous regions, the correlation between rainfall intensity and site characteristics that are commonly associated with heavy rainfall was evaluated. Little correlation was found between rainfall intensity and distance from the closest Great Lake, elevation, and mean annual precipitation. In other words, sampling variability obscures whatever correlation exists. In light of these findings, and the fact that the homogeneity criteria were satisfied with all sites lumped into one region, it was deemed that the State potentially could be treated as one homogeneous region.

To examine the possible adverse effects of treating the State as one region, three other regionalization schemes were evaluated and the resulting quantile estimates compared. Cluster analysis procedures (Hosking and Wallis, 1997) were used to aid in identifying two or three homogeneous regions within the State, with clusters based on the following site characteristics: latitude, longitude, elevation, and mean annual precipitation. Regional quantile estimates were then compared by dividing those derived from the candidate regions by the quantile estimates derived with the State as one region. Differences were deemed to be insignificant for the purposes of this study, so the results derived for the State as one region are recommended.

Consequently, the annual maximum series (AMS) and partial duration series (PDS) results were compiled using the index flood regional frequency analysis procedure

outlined by Hosking and Wallis (1997), with the State considered one homogeneous region. Discordancy, heterogeneity and goodness-of-fit measures for AMS and PDS data were evaluated. The GEV distribution was found to provide the best fit for the AMS data for durations greater than one hour, while the GPA distribution provided the best fit for the PDS data for all durations.

Mathematically, the PDS/GPA model regional quantile estimates are slightly larger than the AMS/GEV quantiles regardless of duration and recurrence interval. This is because the PDS/GPA quantiles are based on more frequent storm events ($F = 1-1/\lambda T$, with $\lambda = 2$) than are the AMS/GEV quantiles ($F = 1-1/T$). Compensating for this mathematically, the PDS index floods (at-site means) tend to be lower than the corresponding means derived from the AMS data, since the PDS means are computed using the $2N$ highest rainfall intensity values, where N is the record length in years. Nonetheless, the AMS results appeared to be slightly higher in magnitude than the PDS results, while the PDS values showed slightly more north-south variation. The small differences in magnitude are easily attributed an empirical factor (1.136) applied to convert the 2-year AMS values to PDS values.

For practical purposes, the AMS/GEV and PDS/GPA models both provide rainfall IDF estimates that are similar in magnitude and variation across the State. Because estimates derived from AMS data rely on empirical factors to convert them to desirable PDS results for shorter recurrence intervals, it is recommended that estimates derived directly from the PDS data be used for the 2-, 5- and 10-year recurrence intervals. Since differences between the two series are negligible for recurrence intervals greater than 10-years, AMS results are recommended for the 25-, 50- and 100-year recurrence

intervals for durations greater than and equal to 1-hour. (These AMS results also account for the positive trend detected in the daily rainfall data for these recurrence intervals.) Since AMS data was not available for the SEMCOG stations, PDS values must be used for all recurrence intervals for the short durations (less than 1 hour).

Final recommended IDF values for each of the 10 climatic sections in Michigan are summarized in tabular form in Appendix B and in graphical form (isopluvial maps) on the accompanying CD. These results are compared to the results of previous studies and to the design IDF values currently used by MDOT. Additional verification of the results is accomplished by a "real data check," in which the number of observed exceedances is compared to the number that would be expected statistically over the period of record.

The results derived in this study are first compared to *Bulletin 71*, *Rainfall Frequency Atlas of the Midwest* (Huff and Angel, 1992), which provided IDF estimates for nine States in the Midwest (including Michigan) for 1-hour to 10-day durations and for recurrence intervals of 2 months to 100 years. For the 1-hour, 2-year storm, results are very similar, with noticeable discrepancies in rainfall depth occurring only in the southwest portion of the Upper Peninsula and the southwest portion of the Lower Peninsula–this study's results are lower by approximately 0.14 and 0.12 inches, respectively. Discrepancies in results are more pronounced for the 1-hour, 100-year storm, with this study's results being 0.20 to 0.80 inches lower across the State than the values given *Bulletin 71*. Furthermore, the results from *Bulletin 71* show a variation in rainfall depths of 1.5 inches across the State, while this study's results show depths varying by less than 0.50 inches. These discrepancies can be explained by differences in

the data and methodology used. For instance, the results in *Bulletin 71* are based on rainfall data collected at 46 daily recording stations, and duration-specific conversion factors were applied to the 24-hour estimates to obtain 1-hour rainfall depths. Furthermore, Huff and Angel (1992) performed an at-site analysis and did not assume that data fit a specific probability distribution, in contrast to the regional frequency analysis done in this study.

Results presented herein are also compared to those given in *Rainfall Frequency for Michigan* (Sorrell and Hamilton, 1990), which updated *TP-40* 24-hour rainfall values for recurrence intervals of 2 to 100 years. For the 24-hour, 2-year storm, results derived herein are within ±0.15 inches of *Bulletin 71* results throughout the State, but are about 0.20 inches lower across the State than those derived by Sorrell and Hamilton (1990). All three sets of results show similar north-south variation in IDF values. For the 24-hour, 100-year storm, results from this study are comparable to those in *Bulletin 71*. (with differences in the northern Upper Peninsula and the southeastern corner of the Lower Peninsula), but they are notably higher than the values given by Sorrell and Hamilton (1990) for the northern parts of the State. These discrepancies are primarily attributed to differences in methodologies. In contrast to the regional frequency analysis with three-parameter distributions and *L*-moment estimators applied herein, Sorrell and Hamilton (1990) derived at-site IDF estimates using the two-parameter Gumbel distribution and method-of-moments estimators.

Finally, revised IDF estimates are compared to the values currently used for design, as given in the MDOT *Road Design Manual*. It is found that current MDOT estimates are significantly larger than those developed in this study. For instance, for 1-

hour storms, current MDOT estimates of 10-year rainfall depths now appear to be closer to 50-year depths. Because it is unclear how the current MDOT IDF estimates were derived, based on adjustments to values derived in *TP-25* and *TP-40*, it is difficult to account for these discrepancies. Nonetheless, the verification of the revised IDF estimates indicates that the values lead the approximately the number of exceedances that would be expected statistically over the period of record. Thus, it appears that structures designed using the current MDOT IDF estimates are safe and reliable structures, but are possibly over-designed.

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1.0 INTRODUCTION

1.1 Objectives and Scope

Due to the occurrence of high-intensity rainfall events more frequently than expected, the Michigan Department of Transportation (MDOT) has deemed it necessary to update the regional rainfall intensity-duration-frequency (IDF) estimates for the State. The overall objective of this study is to revise Michigan's rainfall IDF estimates by: 1) obtaining and screening the most up-to-date gaged rainfall data; 2) delineating homogeneous regions for a regional frequency analysis; 3) fitting an appropriate 3-parameter probability distribution to the observed data; 4) estimating the distribution parameters; 5) spatially interpolating the site-specific scale factor and 6) presenting revised IDF estimates in tabular and graphical forms. Additionally, the development of an interactive geographical information system (GIS) model for display and retrieval of site-specific rainfall IDF estimates is discussed. Rainfall intensity estimates are determined for each of eleven durations (5, 10, 15, 30, 60, 120, 180, 360, 720, 1080, and 1440 minutes) and six recurrence intervals (2, 5, 10, 25, 50 and 100 years).

In contrast to a traditional at-site frequency analysis using the method of moments to estimate distribution parameters, this study applies a regional frequency analysis approach based on *L*-moments, which uses regional information to derive rainfall IDF estimates at any particular site (Hosking and Wallis 1997). Two models for deriving rainfall IDF estimates for the State of Michigan are examined for durations equal to and

greater than one hour. The first is based on fitting the Generalized Pareto distribution (GPA) to Partial Duration Series (PDS) data, and the second is based on fitting the Generalized Extreme Value distribution (GEV) to Annual Maximum Series (AMS) data. For short duration data, the model used for deriving the rainfall IDF estimates for the State of Michigan is the GPA distribution fitted to the PDS data. (AMS data were not available). In addition, methodologies used in previous studies are examined, and trends in Michigan rainfall extremes are investigated.

1.2 Background

In recent years, a number of relatively intense storms have been observed in Michigan. One example is the September 1986 event that produced more than 8 inches of rainfall over a 14,000 square mile area stretching from Lake Michigan to Lake Huron (Sorrell and Hamilton, 1990). In light of this and other events, there is concern that the current IDF estimates are underestimating rainfall amounts. The current estimates for durations less than 24 hours are based on data only through 1958 (Hershfield, 1961), while the majority of the data for the 24-hour estimates are through 1980 (Sorrell and Hamilton, 1990).

In addition, Sorrell and Hamilton (1990) noted that 86 of the 129 daily recording stations in Michigan had recorded a rainfall in excess of the *TP-40* (Hershfield, 1961) 100-year value. More recently, a nine-state study has shown that stations in the Midwest, including those in Michigan, have measured an unexpected number of heavy rainfall events in recent years (Angel and Huff, 1997). For Michigan, it was found that the *TP-40*

24-hour, 100-year value was exceeded 71 times, while only 21 exceedances were expected statistically. Consequently, Angel and Huff (1997) recommend that rainfall frequency studies be updated on a regular basis for maximum reliability.

The risk or probability of extreme rainfall events must be accounted for in structural design of private and public infrastructures. Thus, rainfall IDF estimates are a fundamental necessity in hydrologic and hydraulic design, with their use ranging from the application of the simplest rainfall-runoff relationships to distributed watershed and storm water management modeling. They provide consistent standards for the evaluation of design alternatives (Loucks et al., 2000). For water resource professionals to produce reliable designs, they must be supplied with reliable IDF estimates. Failing to use dependable IDF estimates could place public safety or funds at undue risk.

To quantify an extreme event of a given probability, statistical techniques are employed. The main difficulty in quantifying rare events is a lack of information; often there are not enough data to accurately determine a frequency distribution, or a particular quantile of that distribution, for a specific site. For example, the longest hourly rainfall record for a site in Michigan is 49 years, but from this data an event with a 1% chance of occurring in any given year must be estimated.

It is recognized that the true probability distribution of rainfall at any site is not known. In practice, a simple 2- or 3-parameter distribution is chosen to model the complex occurrence of rainfall. Robust statistical procedures should be used to estimate distribution parameters and obtain accurate quantile estimates. Robust procedures are defined as those whose accuracy is not seriously degraded when the true physical process deviates from the model's assumptions in a plausible way (Hosking and Wallis, 1997).

In hydrology, the probability of an event is often expressed as a return period or recurrence interval. An annual maximum event has a recurrence interval of T years if its magnitude is equaled or exceeded once, on average, every T years. The reciprocal of T ($1/T$) is the exceedance probability of the event, that is, the probability that the event is equaled or exceeded in any one year. For example, the 100-year rainfall has a probability of 0.01, or 1%, of being equaled or exceeded in any one year. It is not to be assumed that only one 100-year event will be observed every 100 years. Rather, on average, around ten 100-year events will be observed during a 1000-year period. It should also be noted that the 100-year event corresponds to the 0.99 quantile (in the upper tail) of the annual maximum frequency distribution.

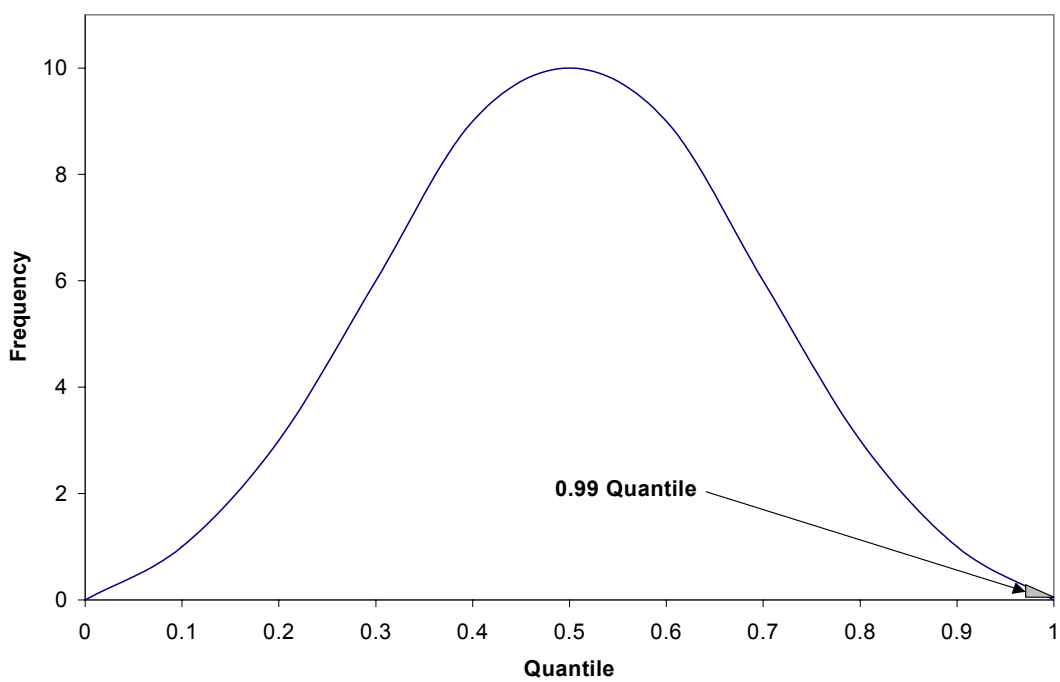

Figure 1.1. Illustration of the 0.99 quantile that corresponds to the 100-yr event of an AMS distribution fit to annual maximum data.

Data for frequency analysis studies can be compiled in several ways. An annual maximum series (AMS) includes only the largest event in each year, while a partial duration series (PDS), or peaks-over-threshold (POT) series, includes all events above a truncation level or threshold. It is assumed that all samples used are independent and identically distributed. A PDS with an equal number of peaks as its corresponding AMS is referred to as an annual exceedance series. While the assumption of independence is usually valid for AMS data, a drawback of the AMS is that it only accounts for the largest event in each calendar year, regardless of whether the second event in a year exceeds the largest events of other years. On the other hand, while long and reliable PDS records are often available, it is difficult to specify criteria for defining independent peaks and determining an appropriate threshold value.

Traditionally, frequency analysis studies have derived estimates from at-site data and have created isopluvial maps from these site-specific estimates using interpolation procedures and judgement. Since the record lengths are often relatively short at gaged sites, regionalization techniques are now used to increase accuracy. Regional frequency analysis "trades space for time" by using data from nearby or similar sites to derive estimates for any given site in a homogeneous climatic region (Stedinger et al., 1993).

A common method for pooling summary statistics from different sites is the index flood procedure. The term "index flood" comes from early studies (e.g., Dalrymple, 1960) that used flood data when implementing the procedure. The main assumption of an index flood procedure is that the sites in a homogeneous region have an identical frequency distribution apart from a site-specific scaling factor, the *index flood*. For

simplicity, the index flood is usually the mean of the site-specific data (Hosking and Wallis, 1997).

The methodology used for deriving rainfall IDF estimates for this study is an index flood based regional frequency analysis approach outlined by Hosking and Wallis (1997). Rather than using traditional methods (i.e., method of moments or maximum likelihood procedures) for compiling site-statistics and estimating distribution parameters, *L*-moments are used. *L*-moments are expectations of certain linear combinations of order statistics (Hosking, 1990) that have been found in many cases to be more efficient and robust than conventional estimation methods.

The first step in this regional frequency analysis approach is to screen the data for gross errors and inconsistencies. The second is to identify homogeneous regions, within which all sites are assumed to have an identical frequency distribution apart from a site-specific scaling factor. It is stressed that delineation of homogeneous regions should be based on site characteristics (e.g., latitude, longitude and elevation) rather than site statistics as homogeneity is tested against site statistics and it would compromise the integrity of the test if site statistics were used both for delineation and for testing (Hosking and Wallis, 1997). The third step is to choose a frequency distribution that not only fits the observed data well, but also yields robust quantile estimates. The fourth and final step is to estimate the regional frequency distribution by combining the weighted at-site parameter estimates to obtain regional parameter estimates. In this study,a procedure known as the *regional L-moment algorithm* is used (Hosking and Wallis 1997). Quantile estimates at a site are then obtained by multiplying the regional quantiles by the index flood. In this study, the index flood is spatially interpolated using geostatistical methods.

2.0 RELATED STUDIES

2.1 Previous Studies

Since Yarnell's seminal publication 65 years ago (Yarnell, 1935), rainfall frequency analysis has evolved substantially due to the advent of computers, increased data availability, and the development of more efficient and robust statistical procedures. Traditionally, annual maximum series data has been fit to a distribution using method-of-moments parameter estimators to obtain quantile estimates at a site, and contours have been drawn subjectively or semi-analytically through the point estimates to obtain regional estimates. In more recent studies (e.g., Julian et al., 1999), a regional frequency analysis procedure using *L*-moments, which are based on probability-weighted moments (Hosking and Wallis, 1997), has been used with regional information to yield more objective and robust quantile estimates for a region. The following is a brief review of the methodologies used in other relevant rainfall frequency studies.

The U.S. Weather Bureau's *Technical Paper 25* (1955) presented a set of rainfall IDF curves for 203 U.S. Weather Bureau stations, 10 of which are in Michigan. *TP-25* provided estimates for durations ranging from 5 minutes to 24 hours, and for recurrence intervals of 2 to 100 years. The Gumbel distribution was fit to annual maximum series data using method-of-moments parameter estimators to derive quantile estimates for each gaged site. These annual series quantile estimates were then transformed to partial duration series values by multiplying by a frequency-dependent empirical factor. For estimating rainfall intensities at ungaged sites, it was recommended that IDF relationships be derived using local data.

Technical Paper 40 (Hershfield, 1961) was an outgrowth of several previous Weather Bureau publications that were prepared under the direction of Hershfield, including *TP-25*. Rainfall IDF estimates used in design up to this point largely came from Yarnell's study (1935), which lacked sufficient data. *TP-40* supplied estimates for durations ranging from 30 minutes to 24 hours and recurrence intervals of 1 to 100 years for the continental United States. Method of moments parameter estimators were again used to fit the Gumbel distribution to annual maximum series data (through 1958) and derive quantile estimates for the 2- and 100-year recurrence intervals for each gaged site. A recurrence interval diagram was used in conjunction with these quantile estimates for estimating values for other frequencies. The line spacing on the diagram was both empirically and theoretically derived. For return periods from 1 to 10 years, the spacing is based on empirical freehand curves drawn through plots of partial duration series data. For return periods from 20 to 100 years, the spacing was derived from fitting annual maximum series data to the Gumbel distribution. As in *TP-25,* the annual series quantile estimates were transformed to partial duration series values by multiplying by a frequency-dependent empirical factor. Because of the arbitrary beginning and ending of a clock hour or calendar day, other empirical factors were also applied to convert from clock-time to actual (time-correct) values. For IDF estimation at ungaged sites, isopluvial maps where constructed for the entire United States, based on the derived at-site IDF estimates.

In the 1970's it was found that the ratios for shorter durations in *TP-40* did not hold true for different recurrence intervals. In addition, an increased demand for hydrologic planning and design for small watersheds prompted the National Oceanic and

Atmospheric Administration (NOAA) to update *TP-40* for short durations. NOAA Technical Memorandum NWS Hydro-35 (*Hydro-35*) (Frederick et al., 1977) provided IDF estimates for durations from 5 to 60 minutes and for return periods from 2 to 100 years for the Eastern and Central United States. The Gumbel distribution was fit to annual maximum series data (through 1972) using method of moments parameter estimators to derive quantile estimates for each gaged site. Equations and nomograms for intermediate duration and return period interpolations were provided. As in the previous two studies, annual series quantile estimates were converted to partial duration series values by multiplying by a frequency-dependent empirical factor. As in *TP-40*, to adjust clock-time results to actual (time-correct) results, a previously derived empirical factor was verified and applied to the resulting IDF estimates. A space-averaging algorithm applied to the at-site IDF estimates was then used in creating isopluvial maps.

More recent studies have been justified on the grounds that the above publications no longer supplied reliable rainfall IDF values, which has been largely attributed to their lack of spatial resolution to adequately depict local variations in rainfall. Other State highway departments (e.g., Dunn, 1986) and agencies (Huff and Angel, 1989; Sorrell and Hamilton, 1990; Huff and Angel, 1992) have deemed it necessary to conduct independent, state- or regional-specific frequency analysis projects.

For Pennsylvania (Dunn, 1986), five regional-specific IDF curves were developed which provided estimates for durations ranging from 5 minutes to 24 hours, and for recurrence intervals of 1.01 to 100 years. Method-of-moments parameter estimators were used to fit partial duration series data (through 1983) to the Log-Pearson Type III distribution to derive quantile estimates at each gaged site. For ungaged sites, five

regions of similar rainfall intensity were delineated. A representative gage from each region was chosen, based on its similarity to the average log-Pearson values of other gages in the region. An IDF curve was then constructed for the chosen gage and applied to its respective region.

To update *TP-40* for 24-hour storms in Michigan, Sorrell and Hamilton (1990) developed IDF estimates for recurrence intervals of 2 to 100 years. The Gumbel distribution was fit to annual maximum series data using method-of-moments parameter estimators to derive quantile estimates at each gaged site. Daily rainfall data were used, with the majority of the records through 1980, except for 15 gages with data through 1987 to incorporate a large event observed in September 1986. As in *TP-40* and other studies, analysis results were multiplied by a frequency-specific empirical factor to convert annual series to partial duration series results, and an additional factor was applied to convert clock-time values to corresponding time-correct values. Isopluvial maps were constructed for each recurrence interval using the at-site IDF estimates. It should be noted that the current MDOT rainfall frequency zones appear to follow these contours.

In an extension of *Bulletin 70* (Huff and Angel, 1989), *Bulletin 71* (Huff and Angel, 1992) updated IDF estimates for nine States in the Midwest (including Michigan) for 1-hour to 10-day durations and for recurrence intervals of 2 months to 100 years. The main motivation for this study stemmed from the need to update *TP-40* for the region. In addition, an apparent climatic trend was deemed to have affected the frequency distributions of extreme rainstorms in Illinois from 1901-1980 (Huff and Changnon,

1987). This was later confirmed by Huff and Angel (1990) for other portions of the Midwest.

In *Bulletin 71*, three procedures for fitting the daily annual maximum series data (through 1986) were examined. The methods of *L*-moments and maximum likelihood were used to fit the data to the Generalized Extreme Value (GEV) distribution. The results of these analyses were compared to a log-log graphical analysis, which the authors refered to as the Huff-Angel method. The Huff-Angel method involves plotting the logarithm of rainfall amounts versus the logarithm of the recurrence intervals and fitting a line through the data points to extrapolate values at higher frequencies at each gaged site. Although this method is more subjective than using other statistical methods, Huff and Angel suggested that the log-log plots allow the analyst to take meteorological and climatological knowledge into consideration. Extrapolation for this method is cut off at or near the 100-year recurrence interval, since the data are not fit to a specific theoretical distribution. The authors stated that the traditional method of moments procedure was not used due to its relatively poor performance compared to *L*-moments and maximum likelihood.

Since the method of *L*-moments was based on a regional approach, the stations in each State were grouped according to the National Weather Service (NWS) climate divisions as shown in Figure 2.1 (with the exception of Indiana and Minnesota, where some regrouping of stations was necessary due to high regional heterogeneity and station discordancy). These divisions have been traditionally accepted as areas of homogeneous climate. Indiana and Minnesota were chosen for comparison of the three methods (GEV

with *L*-moments, GEV with maximum likelihood, and the Huff-Angel method), because of their diverse

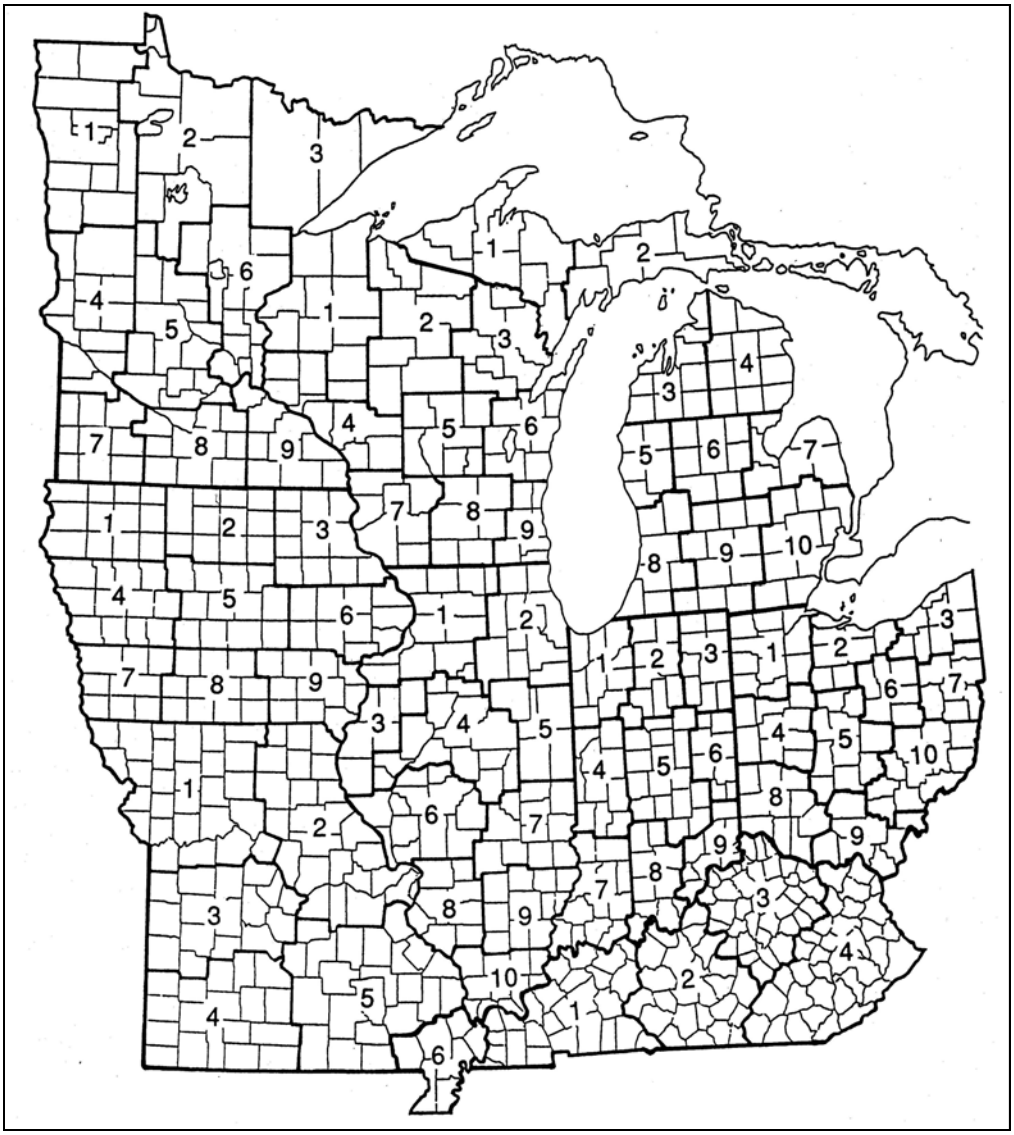

Figure 2.1. NWS divisions of homogeneous climate for the Midwest (Huff and Angel, 1992).

climatic features. After comparing estimates it was found that each method provided results that did not vary significantly from a statistical or meteorological point of view. Overall, the Huff-Angel estimates were between those of the other two procedures. Upon

comparing isopluvial maps, it was concluded that the Huff-Angel spatial patterns better conformed to climatological knowledge of the distribution of rainfall in the Midwest.

Because only daily rainfall data were analyzed, ratios were derived to convert 24-hour values to shorter durations (5 minutes to 18 hours). These ratios were derived using 36 years of data from 34 Illinois stations, plus 21 stations from bordering states, and were found to be in close agreement with those developed in *TP-40.* Duration-specific empirical ratios to estimate intensities for less than the 2-year return period were also provided. The resulting Huff-Angel IDF estimates were then converted from annual series to partial duration series values by multiplying by a duration and frequency-specific factor. Additional duration-specific empirical factors were applied to convert from clock-time to time-correct values. To provide IDF estimates at ungaged sites, isopluvial maps were created from the at-site frequency estimates. For presenting IDF estimates in tabular form, areal mean values were computed for each NWS climate division in each state. Average frequency distributions were developed using all stations within a division and those in surrounding divisions near its boundaries.

More recently, in a report prepared for the Southeastern Wisconsin Regional Planning Commission (SEWRPC), Loucks et al. (2000) updated IDF estimates for durations of 5 minutes to 240 hours and for 2- to 100-year recurrence intervals for 7 counties in and around the Milwaukee area. Due to gage relocation and concern about climate change, several tests for trends and data homogeneity were performed on data compiled at the Milwaukee WSO (Weather Service Office) gage. No evidence was found of any such trends in the data. On account of the complete, high quality, long duration data for the Milwaukee WSO gage, at-site analysis formed the primary basis of

their study. In addition, a regional analysis was undertaken using data from the Milwaukee gage and 14 surrounding gages to supplement the at-site analysis. All frequency analysis procedures were performed on annual maximum series data.

The Generalized Extreme Value (GEV) distribution was fit to the at-site Milwaukee data using the method of *L*-moments. The regional analysis was then performed following the procedure developed by Hosking and Wallis (1997). The seven-county area was treated as one homogeneous region, and the GEV distribution provided the best fit to the regional data. Analyses were carried out on data for the full period of record (1890's – 1998), and for the period from 1940-1998. The resulting quantile estimates were compared for the four scenarios (i.e., at-site and regional analysis for both time periods). As a whole, the full period of record at-site estimates were smallest, while the at-site 1940-1998 estimates were largest (due in part to an outlying event that occurred in August 1986), with the regional estimates in between. It was recommended that the at-site GEV quantile estimates for the full period of record be used for design rainfall for the Southeastern Wisconsin Region. This was mainly due to the regional analysis providing lower estimates than recent observations at Milwaukee. In *TP-40*, estimates were converted from annual series to partial duration series values by multiplying by a frequency-specific, empirically derived value, and additional factors were used to convert short-duration clock-time estimates to actual (time-correct) values.

2.2 Current Studies

Currently, the National Weather Service's Office of Hydrology is updating *TP-40* for the Ohio River Basin (Julian et al., 1998, 1999, 2000, 2001). This study encompasses 13 states and parts of 9 others, including the southern portion of Michigan. Daily, hourly, 15-minute, and N-minute data are being analyzed. Daily data, through December 2000, was obtained from the National Climatic Data Center (NCDC), the U.S. Army Corps of Engineers (COE), and the U.S. Geological Survey (USGS). A total of 3269 daily stations are being analyzed, with the average record length of the stations being 56 years. Hourly data was obtained from the COE through December 2000. There are 984 total hourly stations being analyzed with an average record length of 42 years. Digital N-minute data was obtained from the NCDC through December 2000 in two different data sets that were merged into one containing a total of 76 stations. All data has undergone or is currently undergoing quality control. Quality control includes entering the non-digital data by hand, merging stations and deleting stations with a record length less than twenty years. In order to merge a station, the following criteria must be met: stations must be within 100 feet elevation, be within five miles distance, and contain a gap between records of five years or less, or an overlap in records of five years or less.

Both annual maximum and partial duration series data are being analyzed. The partial duration series contains *N* peaks, with *N* being equal to the actual number of years of record for that station, corresponding to the annual exceedance series. This study is also implementing the regional frequency analysis technique using *L*-moments as outlined by Hosking and Wallis (1997). The project area has been divided into 16

regions based on their respective "extreme precipitation climate." Preliminary analysis has been completed for Illinois, Indiana and Ohio. Analysis was done on each state as a region, and then the states were combined into one region and the results compared. Five three-parameter distributions were tested for an appropriate fit to the data: GEV (Generalized Extreme Value), LNO (Log Normal), GLO (Generalized Logistic), GPA (Generalized Pareto) and PE3 (Pearson Type III). Regardless of duration and region, the best fits for the annual maximum and partial duration series data were provided by the GEV distribution and the GNO distribution, respectively. The results of this analysis demonstrated the effects of regionalization on frequency values. Results for Indiana and Ohio were lower than the regional results, while those for Illinois were higher. However, these departures from the average regional values were determined not to be significant.

A trend and shift statistical analysis was performed on the data to address concerns about climate change on precipitation values. The analysis was performed on annual maximum data from 2755 stations in 22 states. The data was shown to be basically free from linear trends and shifts at a 90% confidence level. There were 1510 stations (or 84%) tested that were free from linear trends, and 437 of 531 (or 84%) tested stations were free from shifts in the mean. Trends and shifts are only significant in about 15% of the stations.

Another important goal of this study is to develop an Internet-Based Geographical User Interface (GUI). The GUI uses a point-and-click interface in which the area of interest can be selected from a shaded relief map. The duration, units, and season can also be selected, and then based on these selections, a color IDF curve and data table are

generated. This system is designed to manage future studies and will also have several supporting web pages.

A published hard copy of the final report for this study is expected to be completed in June of 2002.

3.0 RAINFALL DATA IN MICHIGAN

3.1 Sources and Coverage

This study utilizes 76 hourly and 152 daily rainfall-recording stations throughout Michigan, along with 81 Southeast Michigan Council of Governments (SEMCOG) short duration rainfall-recording stations located in 5 counties in and around the Detroit area (see Figures 3.1 and 3.2). Annual maximum and partial duration series data for 5 to 60 minutes have been compiled from daily records, data for durations from 1 to 18 hours have been compiled from hourly records, and the 24-hour duration data have been compiled from daily records. Annual maximum series data was not used in the short duration analysis as the data contain only rainfall amounts above specified thresholds. SEMCOG recording stations have record lengths ranging from 16 to 38 years, with an average record length of 30 years (through 1999). The hourly recording stations have record lengths ranging from 18 to 49 years, with an average record of 41 years (through 1996). The daily recording stations have record lengths ranging from 21 to 117 years, with an average record of 63 years (through 1996).

Sixteen hourly stations, with recording periods that do not overlap, have been combined to increase record length. The criteria for station combination were that stations must be within 0.07 decimal degrees of latitude and longitude and within 1000 feet in site elevation (Julian et al., 1998). The maximum elevation difference between the stations actually combined was only 99 feet. Due to acceptable areal coverage and adequate record lengths, daily stations were not combined.

For a list of stations see Tables A.1, A.2, and A.3 in the Appendix.

3.2 Criteria for Defining the Partial Duration Series

Since the annual maximum series (AMS) is based on the largest rainfall magnitude in each year, whether it is a calendar year or water year, peak independence is easily maintained. Because a partial duration series (PDS) includes the largest magnitudes regardless of year, some criterion must be determined so that the assumption of independent peaks is upheld. For this study, two peaks in the PDS were assumed to be independent if they were separated by at least the length of the storm duration. For example, each peak in the PDS for the 2-hour duration is separated by at least 2 hours

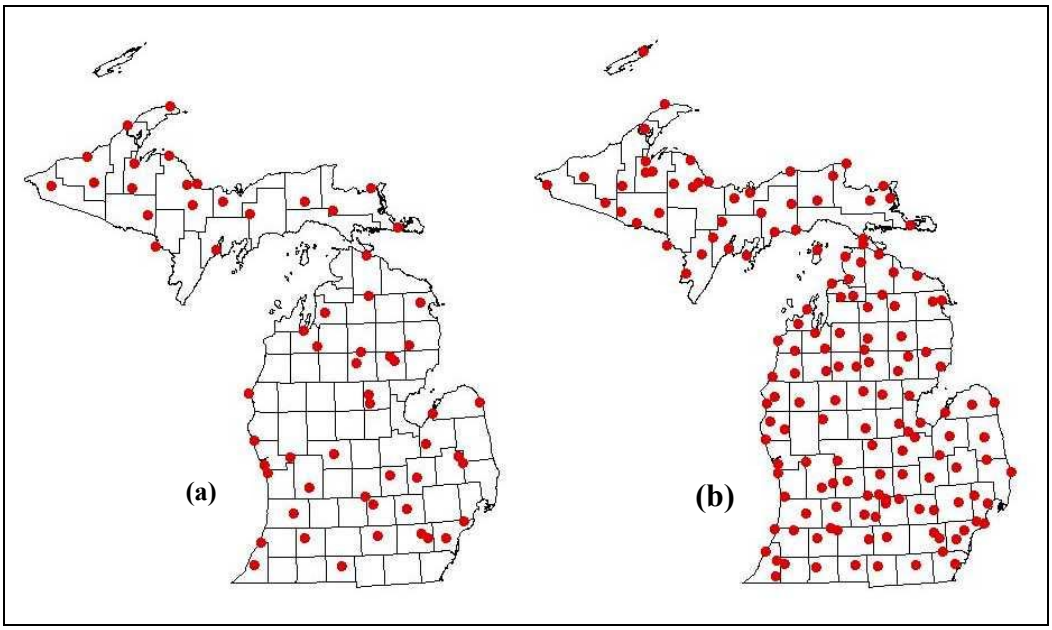

Figure 3.1. Location of selected hourly (a) and daily (b) rainfall recording stations.

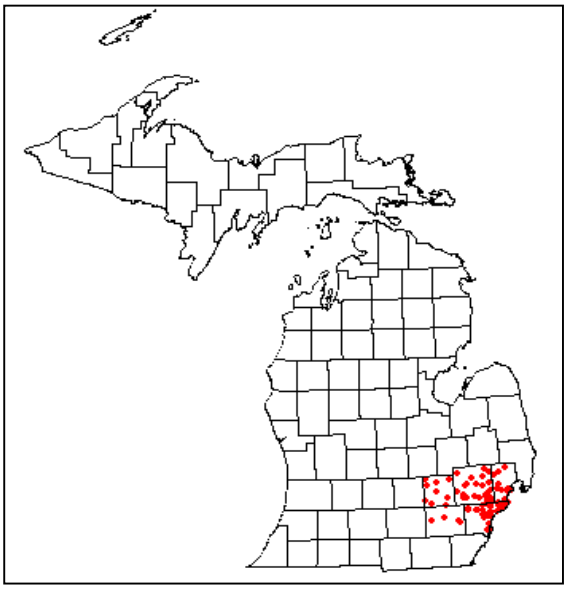

Figure 3.2. Location of SEMCOG recording stations.

from another peak. For each duration and recording station, the number of peaks compiled for the PDS data was 2*N, where N is the number of peaks in the AMS. The actual number of peaks used in the PDS analysis is discussed in Chapter 5.

3.3 Conversion from Annual Maximum to Partial Duration Series Quantiles

Because the PDS can include more than one large event in any particular year, the results from a PDS analysis are thought to be more useful for hydraulic design purposes, especially for return periods shorter than 10 years. However, compiling and processing PDS data is laborious compared to AMS data. In the past, to avoid PDS processing, empirical factors were developed to convert results from an AMS analysis to PDS values. The factors used in this study (see Table 3.1) are those developed for *TP-40* (Hershfield, 1961). These factors are based on a sample of about 200 geographically well-distributed first-order NWS stations (Frederick et al., 1977). The factors in Table 3.1 have been

applied to AMS results in several other studies: *TP-25* (U.S. Weather Bureau, 1955), *Hydro-35* (Frederick et al., 1977), *Rainfall Frequency For Michigan* (Sorrell and Hamilton, 1990), and *Rainfall Frequency in the Southeastern Wisconsin Region* (Loucks et al., 2000). Several studies conducted at the Illinois State Water Survey (Huff and Neill, 1959; Huff and Angel, 1989; Huff and Angel, 1992) have developed factors using stations in Illinois that do not significantly differ from those developed for *TP-40*. In this study, all AMS quantiles, regardless of duration, have been adjusted to PDS quantiles by the factors in Table 3.1. For recurrence intervals greater than 10 years, differences between the two series are negligible. This relationship is shown in Equation 3.1 (Stedinger et al., 1993):

$$T_p = -\frac{1}{\ln\left(1 - 1/T_a\right)} \tag{3.1}$$

where T_p is the average recurrence interval in the PDS, and T_a is the average recurrence interval in the AMS. T_p is less than T_a because more than one event can occur per year in a PDS.

Table 3.1. Factors for converting AMS to equivalent PDS quantiles.

Recurrence Interval (Yrs)	Factor
2	1.136
5	1.042
10	1.010
25	1.000
50	1.000
100	1.000

3.4 Adjustment of Short Duration and Daily Quantiles

The rainfall data used in this study were observed at recording stations that take a reading once every hour (1- to 18-hour durations) or once daily (24-hour duration). Short duration data (5-minute to 30-minute durations) are recorded by Universal Dual-Traverse weighing type gages that produce a trace on a strip chart. An overlay is then used for the various time increments to obtain the short duration readings. Due to the arbitrary beginning and ending of a *clock-hour* or *calendar day*, only a portion of a true 5-minute, 1-hour, or 24-hour storm may be observed. To account for the likely failure of observing a storm's true rainfall (or duration), empirical factors are applied to quantiles from a frequency analysis. The factors in Table 3.2 for the 1-, 2-, and 3-hour durations are taken from Loucks et al. (2000). Their findings are based on an analysis of three NWS first-order stations (Green Bay, Madison and Milwaukee). The factor in Table 3.2 for the 24-hour duration is taken from Huff and Angel (1992), who conducted a study for the Midwest based solely on daily data. Others who have derived and used similar values as those in Table 3.2 are Huff and Neill (1959), Hershfield (1961), Frederick et al. (1977), Huff and Angel (1989), and Sorrell and Hamilton (1990). Both AMS and PDS quantiles derived in this study have been adjusted by the factors in Table 3.2 to reflect actual (*time correct*) values. The effects of event truncation are negligible for the 4- to 18-hour durations, when using hourly data. It is assumed that the effects of event truncation are also negligible for the 30-minute duration when using 5-minute data.

Table 3.2. Factors for converting *clock-hour* quantiles to actual (*time-correct*) quantiles.

Duration (hours)	Factor
5 min	1.13
10 min	1.04
15 min	1.02
1	1.13
2	1.04
3	1.02
24	1.13

4.0 TRENDS IN MICHIGAN RAINFALL DATA

4.1 Background

A typical assumption in any frequency analysis study is that the observed records are stationary over time. That is, year-to-year variations in the data are expected, but the time series does not exhibit major temporal fluctuations or long-term trends. This assumption allows the use of all available historical data with equal weight.

A positive trend over time in rainfall data could have serious design implications. For example, a structure that was designed on the basis of a 10-year event may actually be subject to this event once every 5 years. Recent studies conducted at the Illinois State Water Survey (Huff and Angel, 1990; Angel and Huff, 1997) have investigated trends in rainfall for nine Midwestern States, including Michigan. Angel and Huff (1997) concluded that stations in the Midwest were more likely to experience severe one-day rainfall events ($\geq$ 2 inches) in more recent years. An analysis of the geographic distribution of changes in the annual maximum series data showed areas of increases across the Midwest. In light of these and other findings (Karl et al., 1996; Karl and Knight, 1998; and Kunkel et al., 1999), trend analysis of annual maximum and partial duration series data for Michigan is discussed here.

4.2 Identifying Trends in the Annual Maximum Series

To determine if there has been a shift in the mean of the daily annual maximum series (AMS) over the last 48 years, a non-parametric rank-sum test (e.g., Hirsch et al., 1993) was performed on 27 daily recording stations with least 96 years of record. A non-parametric method was chosen because the data are not assumed to follow a specified

distribution (e.g., most parametric tests assume that data are normally distributed). The data were divided into two 48-year periods, 1901-48 and 1949-96. Several rainfall values at each station had the same magnitude for different years, which resulted in tied ranks. This is accounted for in the formulation of the rank-sum test (e.g., Hirsch et al., 1993). The null hypothesis tested (H_0) was that the second group (1949-96) does not contain larger values than the first group. The results of this analysis show that 22 of the 27 daily recording stations tested have larger annual maximum values from 1949-96. Three stations showed increases at significance levels of $p = 0.15$, one at $p = 0.20$, and five at $p = 0.25$ (one-sided hypothesis test)[1]. At the remaining stations increases were less significant. Five of the 27 stations showed decreases. The spatial distribution of results is shown in Figure 4.1. Because 81% of the stations tested have experienced increases over time, further evaluation was deemed necessary.

For the 27 daily recording stations, the data were again divided into two 48-year periods, 1901-48 and 1949-96. The Gumbel distribution and method of moments estimators were used to derive the 2-year 24-hour (one-day) values from the two different recording periods for each station. It can be seen from Figure 4.2 that the results derived from the 1949-96 data are larger than those derived from the 1901-48 data for 22 of the 27 stations.

In order to investigate a trend in the daily AMS data for all 152 daily recording stations, a plot was made of the daily means from the full period of record versus the daily means from 1949-96. Figure 4.3 shows that the daily AMS means for 1949-96 are consistently larger than those from the full period of record. The results of the analyses

[1] The significance level p can be considered the probability of erroneously rejecting hypothesis H_0. In other words, there is probability p that the more recent data has larger values due to sampling variability alone.

of the daily AMS data indicate that a positive trend is present. While changes in the observation of precipitation, i.e., changes in station exposure, observers, or observation methods, could have an effect over time on individual stations, it is unclear how these increases could be so prevalent across the State. Explanation of this phenomenon, however, is beyond the scope of this study.

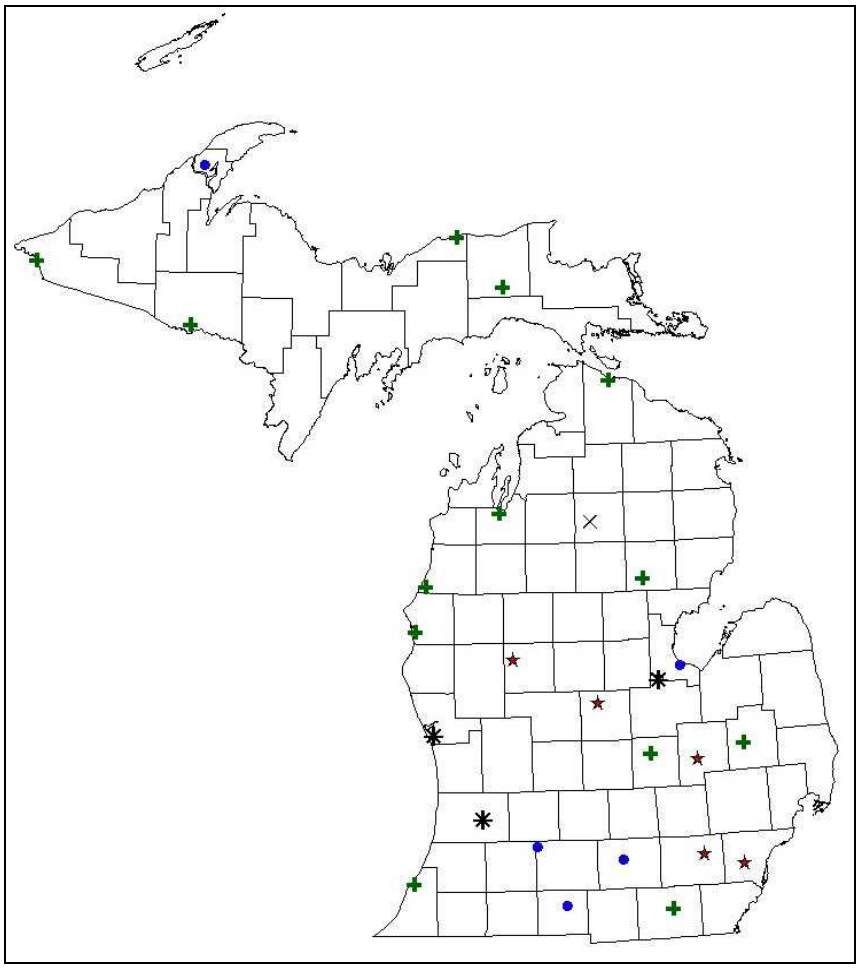

Figure 4.1. Changes in annual maximum time series between two 48-year periods (1901-48 and 1949-96) for daily rainfall. (+) Stations with increases over time; (∗) Stations with significant increases at p = 0.15; (×) Stations with significant increases at p = 0.20; (★) Stations with significant increases at p = 0.25; (•) Stations with decreases over time.

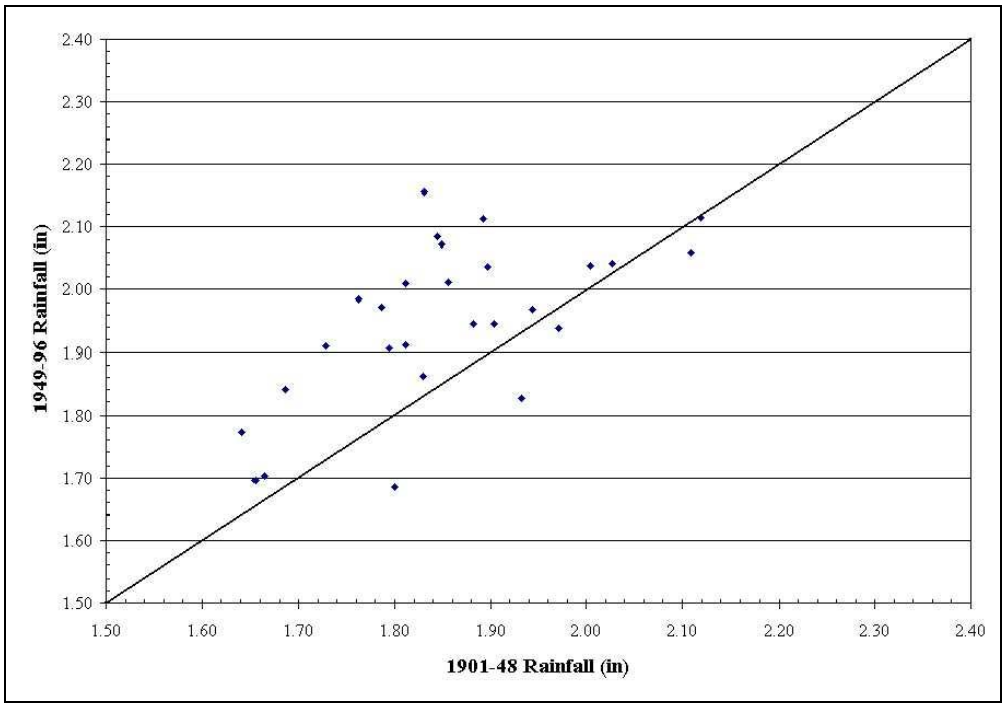

Figure 4.2. Comparison of the AMS 2-year 24-hour rainfall values for 1901-48 and 1949-96, at 27 daily recording stations.

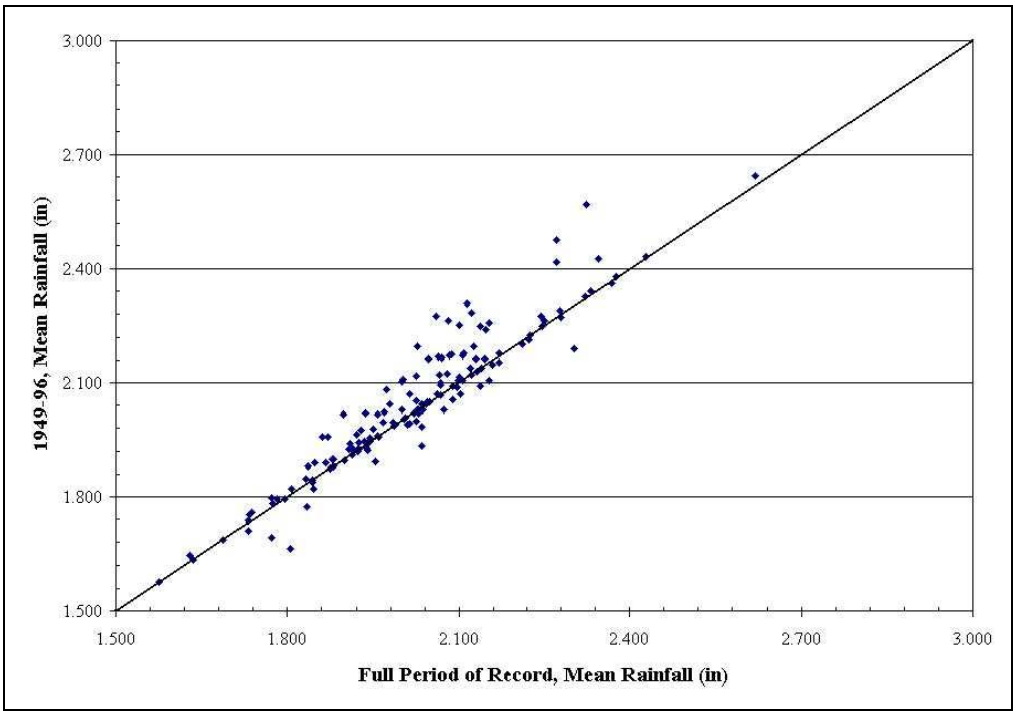

Figure 4.3. Comparison of the AMS means for the full period of record and 1949-96, at 152 daily recording stations.

The increase in the daily AMS data over time presents a challenge to estimating rainfall values for different recurrence intervals. If the entire period of record is used, there may be an underestimation of (future) rainfall IDF values. However, if estimates are derived using only observations from the latter part of the century (1949-96), important data for estimating intensities with longer recurrence intervals (i.e., the 100-year event) are lost. To address this problem, Huff and Angel (1989) weighted the expected rainfall amounts for the 1901-83 period by a factor calculated as the ratio of the 1941-80 rainfall IDF estimates to those for the entire 1901-83 period at each of 61 stations in Illinois. Mean ratios were then calculated for each of the 10 NWS climatic zones in Illinois, and these average values were used to adjust the station values derived from the 1901-83 data. Average ratios were used to reduce the effect of random sampling fluctuations between the 61 individual stations. Huff and Angel (1989) rationalized that this procedure allowed, for example, for the 100-year event to be derived using all available information, while still taking into account the observed trend. Because a positive trend has been identified in the daily AMS data for Michigan, similar adjustment may be necessary to put greater weight on the more recent rainfall events.

Similar tests were conducted on 25 hourly recording stations with at least 46 years of record for the 1- and 12-hour durations. A rank-sum test (e.g., Hirsch et al., 1993) was conducted, identical to that performed on the daily data. The 1- and 12-hour data were divided up into two groups, 1951-73 and 1974-96. The results of the rank-sum test for the 1-hour duration showed that 19 of the 25 hourly recording stations tested have observed lower values from 1974-96; while only six stations showed increases in the

values observed (two at $p = 0.25$). The results for the 12-hour duration are similar, with 16 stations showing decreases in the values observed and just nine stations showing increases (three at $p = 0.20$).

To further investigate the possibility of a trend being present in the hourly data, a quantile comparison was performed. The Gumbel distribution and method of moments estimators were used to derive 2-year rainfall estimates from data for the full period of record (1951-96) and from 1974-96. The plots in Figures 4.4 and 4.5 show that the 2-year estimates from the last half of the recording period are not larger than those from the full period of record.

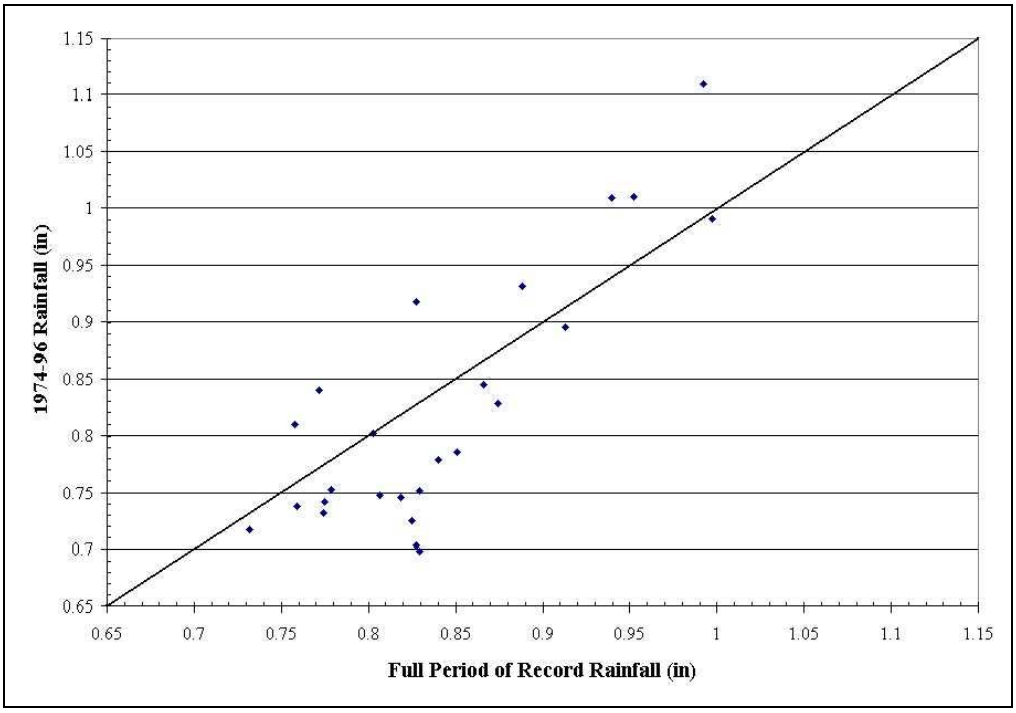

Figure 4.4. Comparison of the AMS 2-year 1-hour rainfall values for the full period of record (1951-96) and 1974-96, at 25 hourly recording stations.

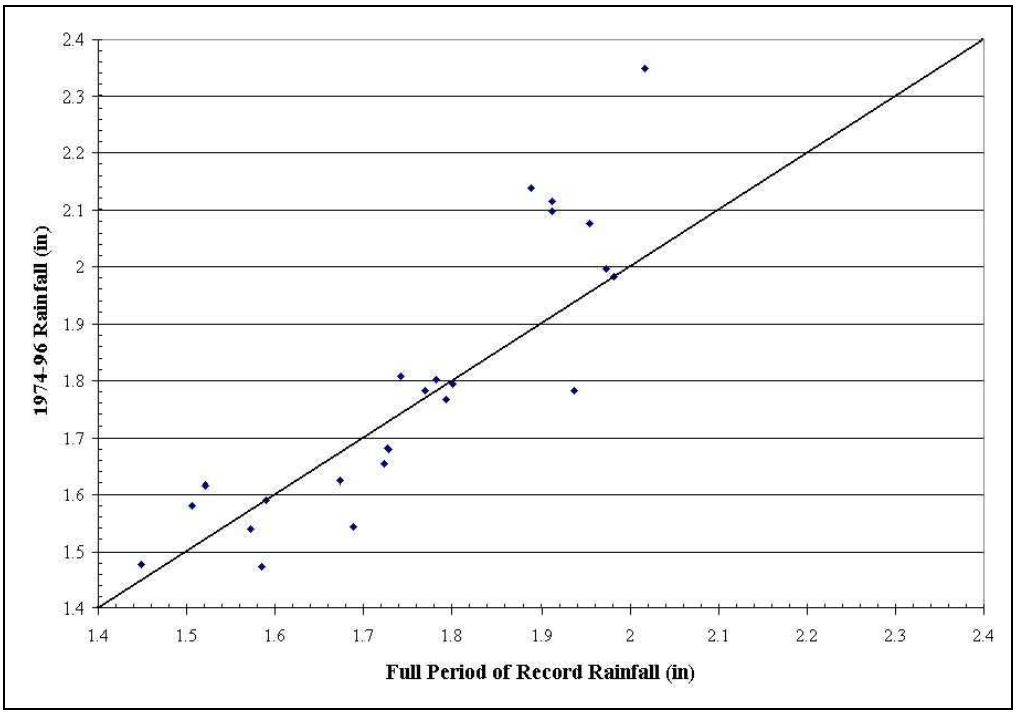

Figure 4.5. Comparison of the AMS 2-year 12-hour rainfall values for the full period of record (1951-96) and 1974-96, at 25 hourly recording stations.

The results of the rank-sum test and the quantile comparison for the 1- and 12-hour durations have shown that no positive trend is present in the hourly data. Furthermore, since all of the hourly data are from the last half of the century (1948-96), it is deemed that this data represents current Michigan rainfall frequency estimates and can be treated with equal weight to produce reliable IDF estimates for the 1- to 18-hour durations.

4.3 Identifying Trends in the Partial Duration Series

To investigate the possibility of trends in the partial duration series (PDS) data, a trend analysis was conducted on daily, hourly, 10- and 30-minute data. For the daily data, a time series of the number of rainfall events that exceeded 2 inches or more and 4 inches or more were plotted and analyzed (see Figures 4.6 and 4.7). These figures are based on

50 daily recording stations with at least 70 years of record. One would expect year-to-year variability with no long-term trends in these time series. However, for the number of daily events that equaled or exceeded 2 inches (see Figure 4.6), a positive trend was indicated (p = 0.01) (e.g., Salas, 1993). This indicates an approximate 53% increase in the annual number of daily rainfall events of 2 inches or more during the 1927-96 period. For the number of daily events 4 inches or more (see Figure 4.7), a positive trend was also indicated (p = 0.10). There appears to be an increase of about 165% in these severe events over the 1927-96 period.

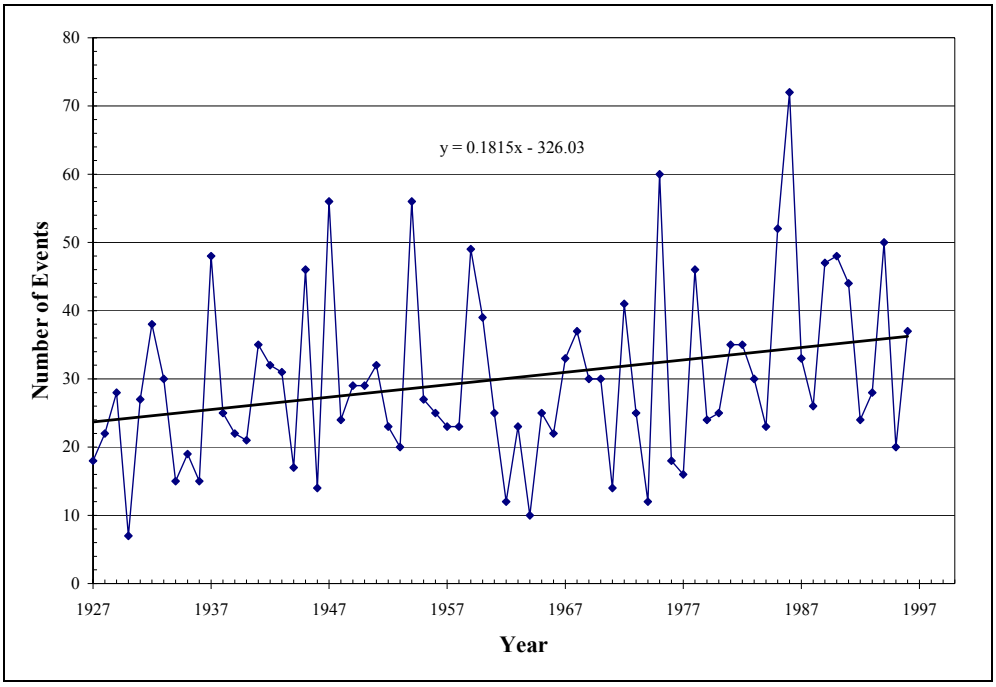

Figure 4.6. Number of daily rainfall events that equaled or exceeded 2 inches; non-zero (positive) slope indicated at p = 0.01.

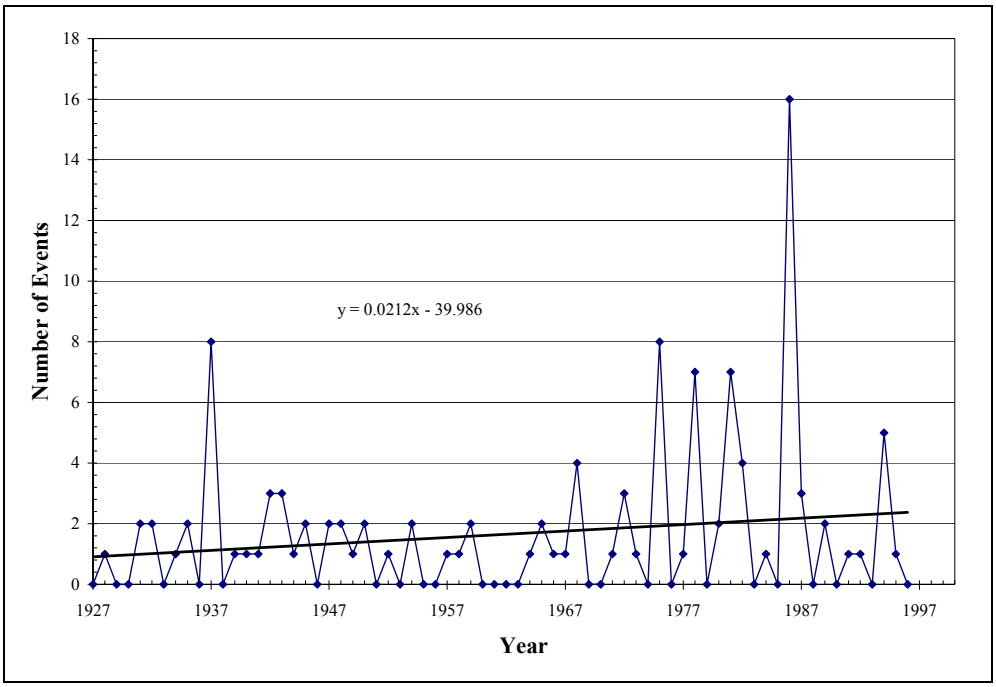

Figure 4.7. Number of daily rainfall events that equaled or exceeded 4 inches; non-zero (positive) slope indicated at p = 0.10.

Time series data of the number of rainfall events for the 10-minute data that exceeded 0.75 inches or more and 1 inch or more were also plotted and analyzed (see Figures 4.8 and 4.9). The data used were from 77 SEMCOG stations that at least 16 years of data. Again, one would expect no long term trends in the time series, yet for the number of events that equaled or exceeded 0.75 inches (see Figure 4.8), a negative trend was indicated (p = 0.01). This shows that there has been approximately a 41% decrease in the number of annual 10-minute storm events of 0.75 inches or more in the 1961-99 time period. A negative trend was also illustrated (see Figure 4.9) in the number of events that equaled or exceeded 1 inch (p = 0.02). From this it can been seen that there was an estimated 71% decrease in the annual number of 10-minute storm events of 1 inch or more in the time period of 1961-99.

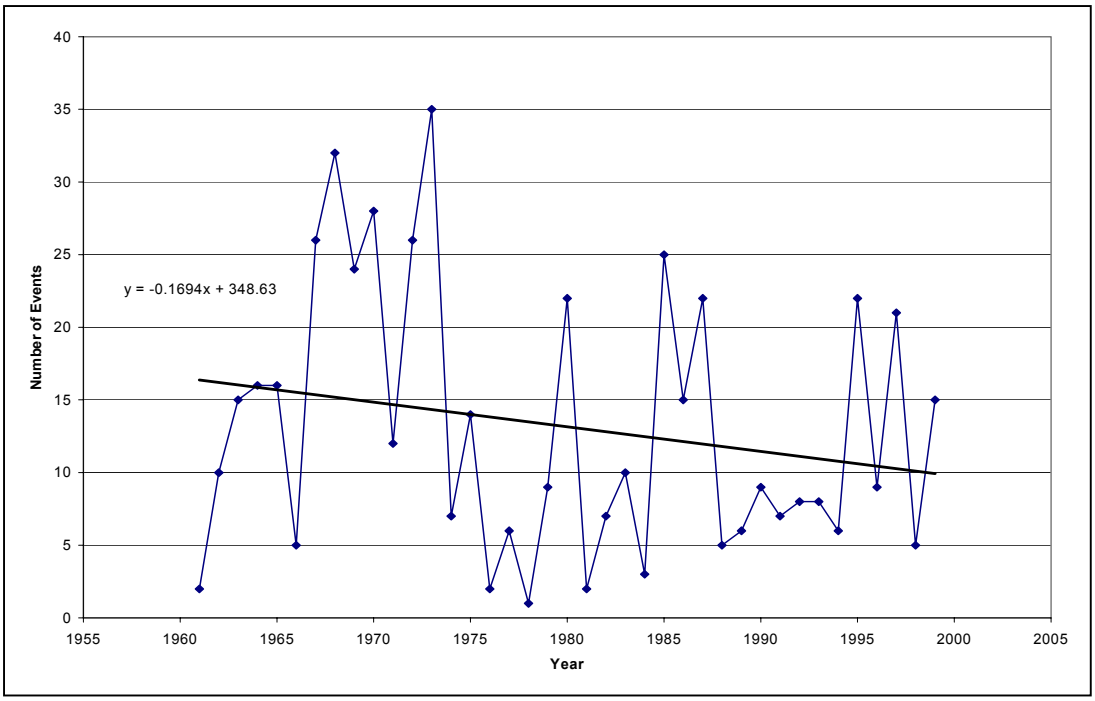

Figure 4.8. Number of 10-minute rainfall events that equaled or exceeded 0.75 inches; negative slope indicated at p = 0.1.

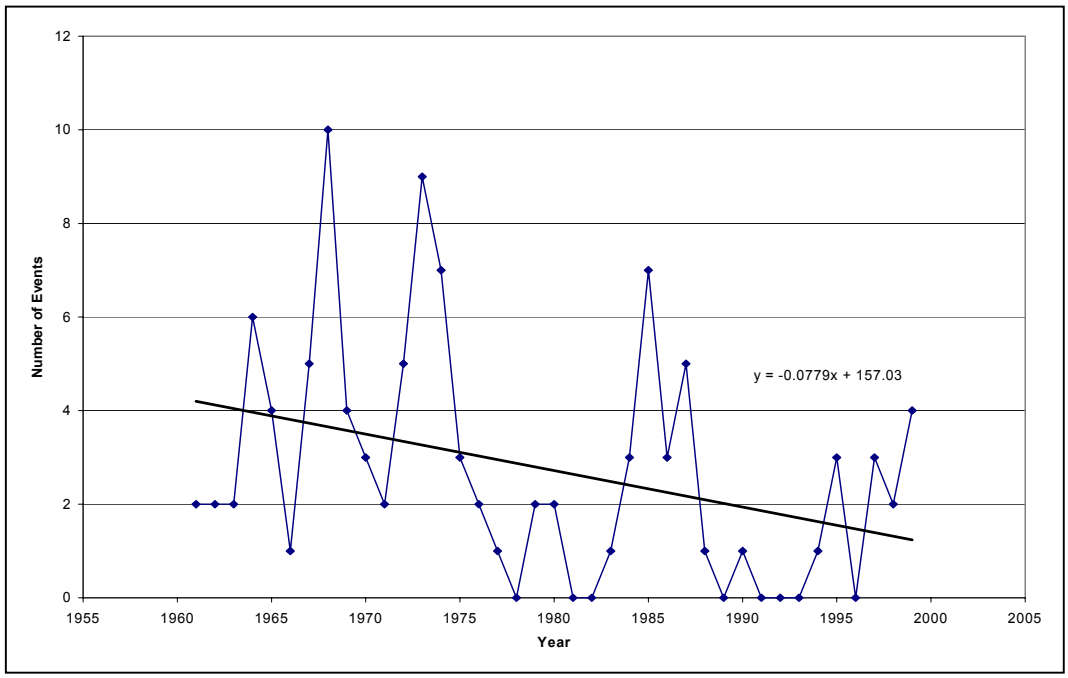

Figure 4.9. Number of 10-minute rainfall events that equaled or exceeded 1 inch; negative slope indicated at p = 0.02

This trend was also seen in the analysis of the 30-minute data. For the 30-minute duration, plots were made of the data that equaled or exceeded 1.75 inches and the data that equaled or exceeded 2 inches (see Figures 4.10 and 4.11). Once again, a negative trend was indicated by the data (p = 0.306 for 1.75 inches, p = 0.258 for 2 inches). From this, it appears that there was a 26% decrease in the annual number of 30-minute storm events of 1.75 inches or more and a 35% decrease in the annual number of 30-minute storm events of 2 inches or more for the period of 1961-99.

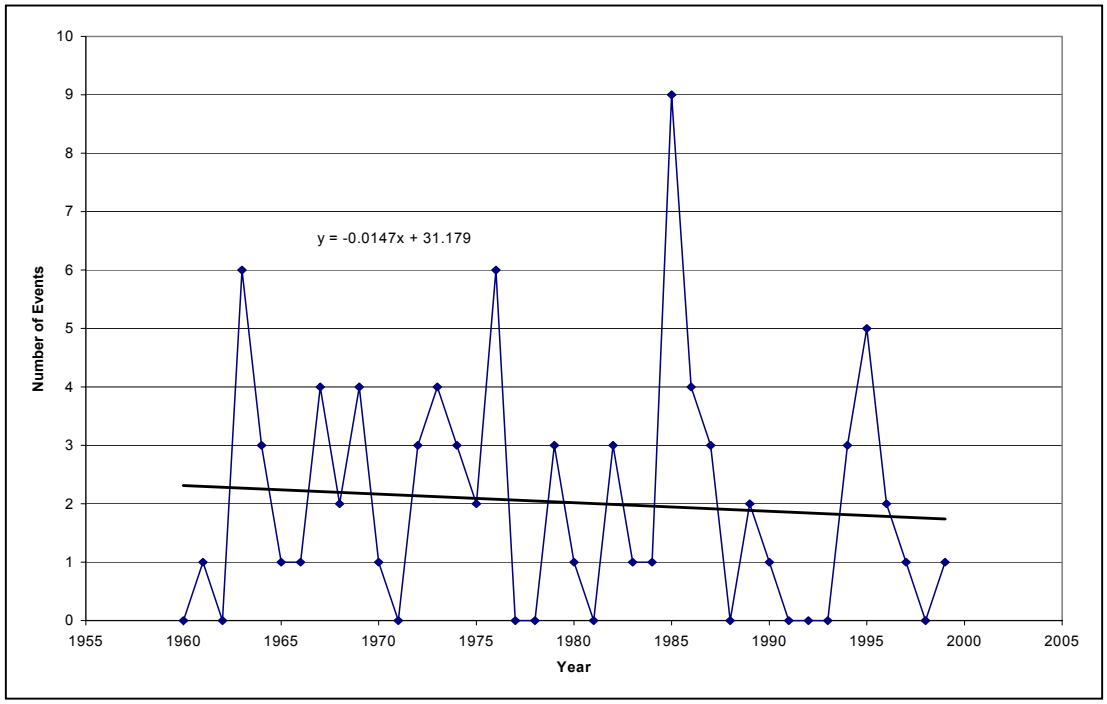

Figure 4.10. Number of 30-minute rainfall events that equaled or exceeded 1.75 inches; negative slope indicated at p = 0.306

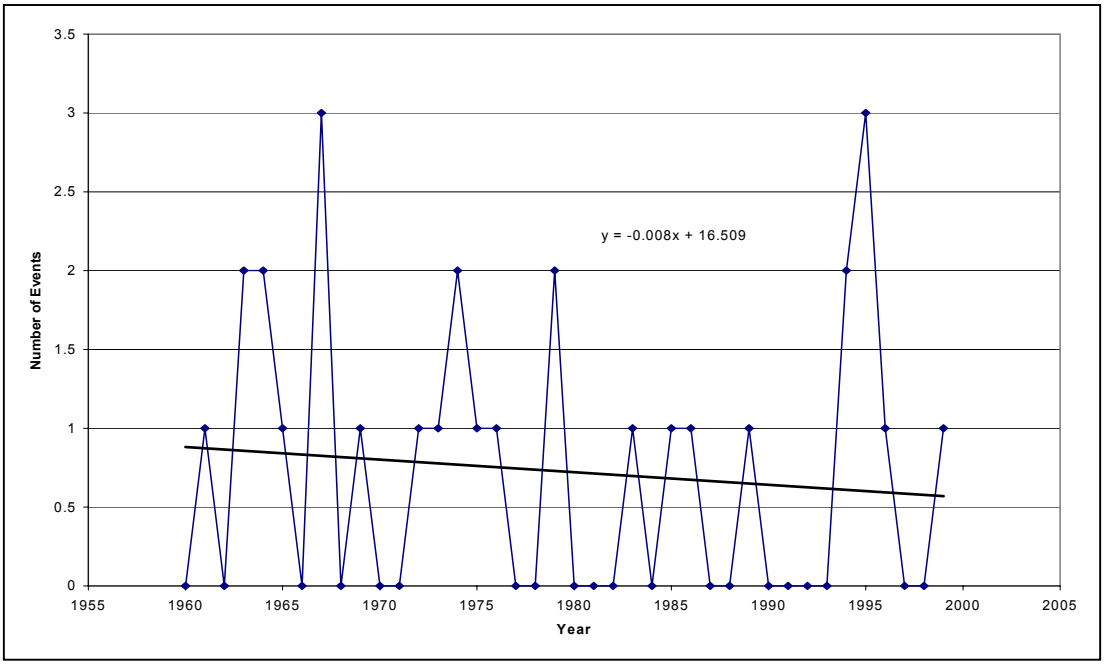

Figure 4.11. Number of 30-minute rainfall events that equaled or exceeded 2 inches; negative slope indicated at p = 0.258

4.4 Evaluating Trends in Partial Duration Series Data

To examine the effect of the observed trend on daily (24-hour) PDS quantile estimates, a comparison was made of quantiles derived from the full period of record (1927-96) and those from 1960-96. The Generalized Pareto distribution and *L*-moment estimators were used to derive the quantiles at each of the 50 stations for the two time periods. The 1960-96 quantiles were then divided by the quantiles from the full period of record for each recurrence interval at each station. The ratios from the 50 daily recording stations were then averaged to obtain the mean ratios shown in Table 4.1. For recurrence intervals greater than 10 years, these average ratios suggest that quantile estimates from 1960-96 are 1 to 2% higher than those generated from the full period of record. If these 1 to 2% differences are deemed to be important for these recurrence intervals, the quantiles

from the full period of record could be increased by these ratios. However, for the purposes of this study, the noted differences in quantiles were deemed to be insignificant. Therefore, for the daily PDS, no measure will be taken to place more weight on observations recorded in the latter years of the century.

Table 4.1. Mean ratios of 1960-96 quantiles over those from the full period of record (1927-96), derived from daily PDS data at 50 daily recording stations.

Recurrence Interval (Yrs)	Mean Ratio
2	1.00
5	1.00
10	1.01
25	1.01
50	1.02
100	1.02

To investigate trends in the hourly PDS data, a quantile estimate comparison was made for the 1- and 12-hour durations. Again, the Generalized Pareto distribution and *L*-moment estimators were used to derive quantiles for 25 hourly recording stations for two time periods. Ratios were then calculated by dividing quantile estimates derived from 1974-96 data by those derived from the full period of record (1951-96). The ratios were then averaged to obtain the mean ratios shown in Tables 4.2 and 4.3. The mean ratios for the 1-hour duration (Table 4.2) show that the quantile estimates from 1974-96 do not differ from those generated from the full period of record. The mean ratios for the 12-hour duration (Table 4.3) do not show a difference for recurrence intervals less than or equal to 25 years. However, for the 50- and 100-year recurrence intervals, the estimates for 1974-96 were 5% and 8% larger, respectively, than the values derived from the full

period of record. Although this may be cause for concern, these differences can easily be attributed to sampling variability, or the uncertainty in quantile estimation for such rare events.

Table 4.2. Mean ratios of 1974-96 quantiles over those from the full period of record (1951-96), derived from 1-hour PDS data at 25 hourly recording stations.

Recurrence Interval (Yrs)	Mean Ratio
2	0.99
5	0.99
10	0.99
25	0.99
50	1.00
100	1.01

Table 4.3. Mean ratios of 1974-96 quantiles over those from the full period of record (1951-96), derived from 12-hour PDS data at 25 hourly recording stations.

Recurrence Interval (Yrs)	Mean Ratio
2	0.99
5	0.99
10	1.00
25	1.02
50	1.05
100	1.08

Trends were also investigated in the short duration data by making a quantile estimate comparison for the 10- and 30-minute data. As in the daily and hourly comparisons, the Generalized Pareto distribution and L-moment estimators were used to derive quantiles for 75 SEMCOG short duration stations for two time periods. The full

period of record for the short duration stations is from 1961-99. A comparison was made of the quantiles from the full period (1961-99) and from a more recent period (1980-99) by dividing the quantile estimates calculated from the 1980-99 data by the full period of record (1961-99) data. An average was then taken of the ratios to calculate the mean ratios that can be seen in Tables 4.4 and 4.5. The mean ratios for the 10-minute duration (Table 4.4) show that the quantile estimates from 1980-99 are slightly less than the quantile estimates for the full period. In fact, the 1980-99 estimates are about 6% smaller for the 50- and 100-year recurrence intervals. A similar trend can be seen in the mean ratios for the 30-minute duration data (Table 4.5). Again the quantile estimates from 1980-00 are slightly less than the quantile estimates for the full period. The greatest difference between the two is that the 1980-99 estimate is about 5% smaller than the full period estimate for the 50- and 100-year recurrence intervals.

Table 4.4. Mean ratios of 1980-99 quantiles over those from the full period of record (1961-99), derived from 10-minute PDS data at 75 SEMCOG stations.

Recurrence Interval (Yrs)	Mean Ratio
2	0.98
5	0.97
10	0.96
25	0.95
50	0.94
100	0.94

Table 4.5. Mean ratios of 1980-99 quantiles over those from the full period of record (1961-99), derived from 30-minute PDS data at 75 SEMCOG stations.

Recurrence Interval (Yrs)	Mean Ratio
2	0.98
5	0.97
10	0.97
25	0.96
50	0.95
100	0.95

It must be noted, for the quantile estimates derived from the 1974-96 data, that only 23 years of data were used to derive estimates for the 50- and 100-year recurrence intervals for these hourly comparisons. Because of the short record length, a large amount of variability is present in estimating these values. This also holds true for the quantile estimates derived from the 1980-99 data. For the 12-hour duration, several large events where recorded in 1978 and 1987 at the 25 hourly stations. Because of the data split (1951-73 and 1974-96), these large events were given greater weight, thus contributing to the increases at the 50- and 100-year recurrence intervals noted in Table 4.3. Taking these considerations into account, and recognizing that there were no significant differences in the quantile estimates generated from the daily and 1-hour PDS data, no measures are taken place more weight on observations from the latter portion of the recording period for the hourly PDS data. For the short duration data, the quantile estimates were actually less for the 1980-99 period, therefore no weighting was needed for the latter portion of the recording period.

4.5 Summary

The purpose of this chapter was not to speculate about global or regional climate change, but rather to identify trends in Michigan rainfall data and account for those trends in rainfall IDF estimation. Analyses indicate a positive trend over time in the daily AMS data. It is recognized that some adjustment may be necessary to put greater weight on the more recent daily rainfall events. Little evidence of such trends was identified in the hourly AMS data; therefore no adjustments are deemed necessary. A negative trend over time was indicated in the short duration (10- and 30-minute data).

A temporal analysis of the daily PDS data revealed significant increases in the frequency of heavy rainfall in Michigan over a 70-year period (1927-96). In light of this, quantile estimates derived from the 1960-96 period were compared with those derived from the full period of record. No significant differences were found. As a result, no measures will be taken to account for the trend in the daily PDS data. To identify trends in the hourly PDS data, a quantile comparison was again conducted. For the 1- and 12-hour durations, quantile estimates derived from the 1974-96 period were compared with those derived from the full period of record, and significant differences were observed at the 50- and 100-year recurrence intervals for the 12-hour duration. However, taking into account sampling variability, and the fact that there were no significant differences in the daily and 1-hour quantile comparisons, these differences will not be accounted for in rainfall IDF estimation.

Similar results were also found for the short duration data. For the 10- and 30-minute durations, the quantile estimates derived from the 1980-99 period were found to be lower than those from the full period of record. These differences will not be

accounted for in the rainfall IDF estimation, as sampling variability and the short period of record may easily account for this difference.

5.0 REGIONAL RAINFALL FREQEUNCY ANALYSIS

5.1 Introduction

The methodology used for deriving rainfall IDF estimates for the State of Michigan is an index flood based regional frequency analysis approach as outlined by Hosking and Wallis (1997). The procedure assumes that sites from a homogeneous region have an identical frequency distribution apart from a site-specific scaling factor. Rather than using traditional methods (i.e., method of moments or maximum likelihood procedures) for compiling site-statistics and estimating distribution parameters, *L*-moments are used. *L*-moments are expectations of certain linear combinations of order statistics (Hosking, 1990) that have been found to be more efficient and robust than conventional estimation methods (e.g., Hosking, 1990; and Madsen et al., 1997). Two models based on this methodology are presented: a Generalized Pareto distribution fitted to partial duration series data (PDS/GPA Model), and a Generalized Extreme Value distribution fit to annual maximum series data (AMS/GEV Model).

5.2 Reasons for a Regional Analysis

Traditionally, frequency analysis studies have derived estimates from at-site data and created isopluvial maps from these site-specific estimates. Because record lengths are often relatively short at gaged sites (i.e., it is difficult to accurately estimate a 100-year event from 49 years of data), regionalization techniques are used to increase accuracy. Regional frequency analysis "trades space for time" by incorporating hydrologic data from nearby or similar sites to derive estimates for any given site in a homogeneous region (Stedinger et al., 1993). The concept of trading space for time is

illustrated in Figures 5.1 and 5.2. Figure 5.1 depicts the fit of the Generalized Extreme Value (GEV) distribution to 2-hour annual maximum rainfall data observed at the Hancock, MI station. Figure 5.2 illustrates the fit of the GEV to 2-hour annual maximum rainfall data observed at 10 stations in Michigan. The pooled data in Figure 5.2 allow a much better fit of the distribution than do the data from the single site in Figure 5.1. Because more data are included in a regional analysis, there is potential for greater accuracy in the final quantile estimates. In addition, recent research has shown that even when moderate regional heterogeneity is present, a regional analysis will still yield much more accurate quantile estimates than an at-site analysis (Lettenmaier et al., 1987; Hosking and Wallis, 1988; Potter and Lettenmaier, 1990; Hosking and Wallis, 1997). As opposed to streamflow data, where characteristics often differ from catchment to catchment, regionalization is easier to employ for rainfall data in regions without substantial relief because characteristics are often uniform over a large area (Stedinger et al., 1993). For practical purposes this is the case for Michigan.

5.3 Definition of L-moments

L-moments are defined as expectations of certain linear combinations of order statistics (Hosking, 1990). They are analogous to conventional moments with measures of location (mean), scale (standard deviation), and shape (skewness and kurtosis). Because *L*-moments are linear combinations of the ranked observations and do not involve squaring or cubing the observations as is done for the conventional method of moments estimators, they are less sensitive to outliers. The *L*-moment estimators of the coefficient of variation (*L*-CV) and skewness (*L*-skewness) are also nearly unbiased and are nearly normally distributed. In contrast, the method of moment estimators of the

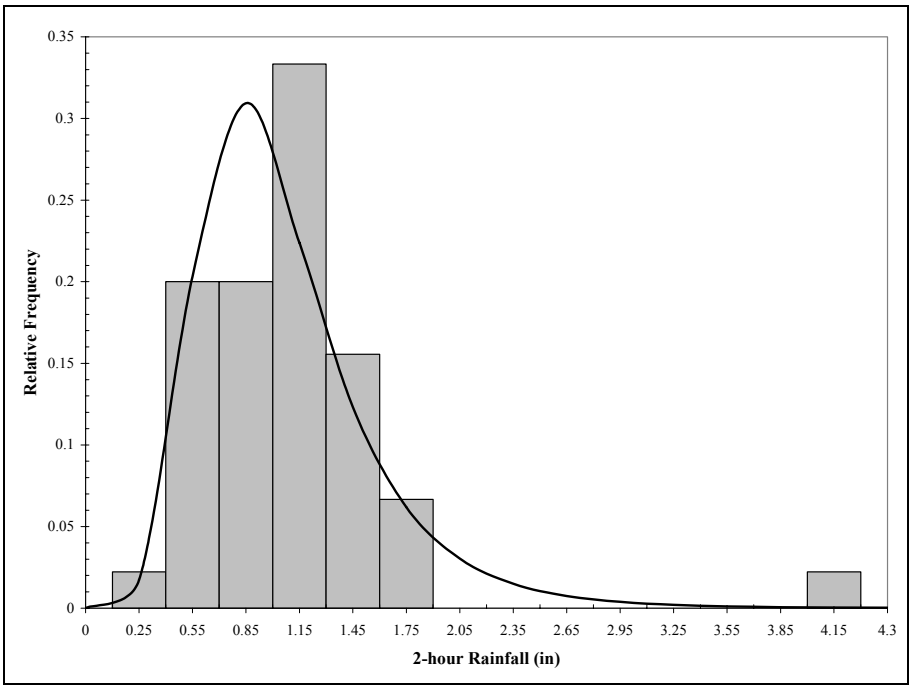

Figure 5.1. Generalized Extreme Value probability density function (PDF), fit to histogram of 2-hour rainfall data from Hancock, MI station (n=45).

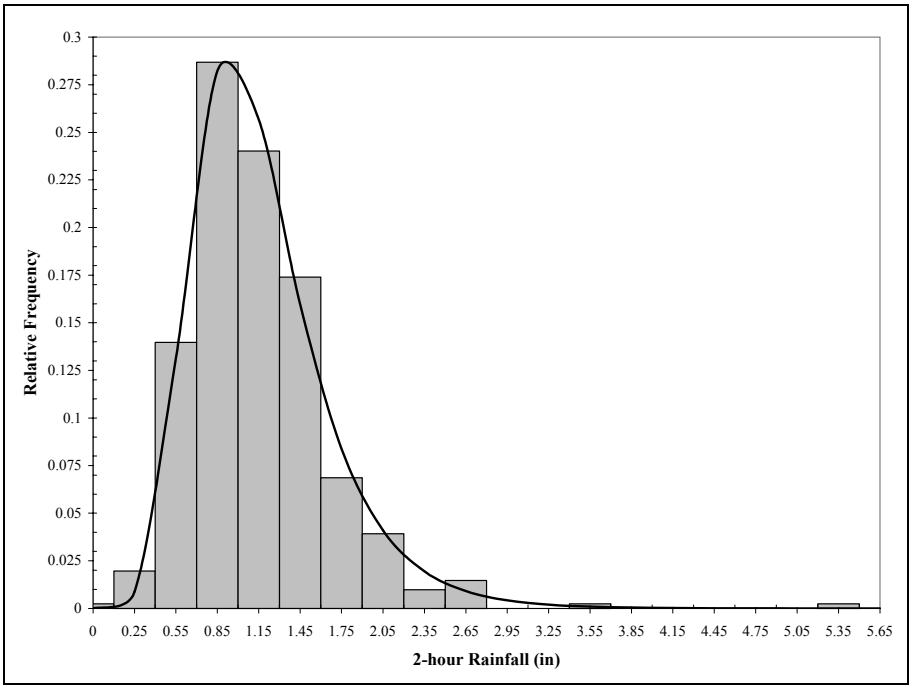

Figure 5.2. Generalized Extreme Value probability density function (PDF), fit to histogram of 2-hour rainfall data from 10 stations in Michigan (n=408).

coefficient of variation and skewness are highly biased and highly variable in small samples. Method of moments estimators also give undue weight to outliers, which can mask the information provided by the other observations in the data set. Wallis et al. (1974), Hosking (1990) and Hosking and Wallis (1997) discuss these issues in greater detail. Hosking (1990) has also shown that parameter estimates obtained from *L*-moments are often more accurate in small samples than those derived using maximum likelihood procedures. For a number of hydrologic applications, *L*-moments are efficient estimators of the characteristics of hydrologic data and of a distribution's parameters (Stedinger et al., 1993).

L-moments are derived from modifications to *probability-weighted moments* (PWMs), which were developed by Greenwood et al. (1979). For a random variable *X*, PWMs can be defined as (Stedinger et al., 1993)

$$\beta_r = E\left\{X\left[F(X)\right]^r\right\}, \tag{5.1}$$

where *F(X)* is the cumulative distribution function (cdf) for *X*. PWMs are the expectation of *X* multiplied by powers of *F(X)*. Landwehr et al. (1979), Hosking et al. (1985) and Hosking and Wallis (1987) have used PWMs as the basis of methods for estimating parameters of probability distributions. However, PWMs are difficult to interpret directly as measures of the scale and shape of a probability distribution. This information is contained in linear combinations of the PWMs, or *L*-moments.

5.4 Sample L-moments

Population *L*-moments are defined for a probability distribution, but in practice they must be estimated from an observed sample. Estimation is based on a sample of size

n, arranged in ascending order (i.e., $x_{1:n} \leq x_{2:n} \leq \ldots \leq x_{n:n}$ is the ordered sample). L-moment estimation begins by estimating the population probability weighted moment β_r. An unbiased estimator of β_r is (Hosking and Wallis, 1997):

$$b_r = n^{-1} \sum_{j=r+1}^{n} \frac{(j-1)(j-2)...(j-r)}{(n-1)(n-2)...(n-r)} x_{j:n} \tag{5.2}$$

From b_r the sample L-moments are given by (Hosking and Wallis, 1997):

$$\ell_1 = b_0 \tag{5.3}$$

$$\ell_2 = 2b_1 - b_0 \tag{5.4}$$

$$\ell_3 = 6b_2 - 6b_1 + b_0 \tag{5.5}$$

$$\ell_4 = 20b_3 - 30b_2 + 12b_1 - b_0 \tag{5.6}$$

$$\ell_5 = 70b_4 - 140b_3 + 90b_2 - 20b_1 + b_0 \tag{5.7}$$

where ℓ_1 and ℓ_2 are respectively measures of the sample mean and scale of the distribution. The remaining L-moments are used to determine the sample L-moment ratios, which are (Hosking and Wallis, 1997):

$$t_r = \ell_r / \ell_2 \tag{5.8}$$

where t_3 and t_4 are respectively the sample L-skewness and L-kurtosis. The sample L-coefficient of variation (L-CV) is given by (Hosking and Wallis, 1997):

$$t = \ell_2 / \ell_1 . \tag{5.9}$$

The estimators t_r and t are not unbiased, but their biases are very small in moderate or large samples (Hosking, 1990). It has been shown that they are more robust to outliers and are more efficient than the method of moments estimators of the coefficient of variation, skewness and kurtosis (Hosking, 1990; Hosking and Wallis, 1997).

5.5 Regional Rainfall Frequency Analysis Methodology

The following procedure is that outlined by Hosking and Wallis (1997). The main steps are to screen the data, identify homogeneous regions, chose a frequency distribution, and estimate the parameters of the chosen distribution. These steps are discussed in detail below.

Screening the Data. The first step in any statistical investigation is to check that the data are suited for the analysis. Tests for gross outliers, inconsistencies, shifts, and trends (see Chapter 4) are ways to check the appropriateness of the data. Additionally, Hosking and Wallis (1997) present a discordancy measure based on the *L*-moments of the sites' data. The discordancy measure is a single statistic based on the difference between the *L*-moment ratios of a site and the average *L*-moment ratios of a group of similar sites and can be used to identify erroneous data.

The formulation of the discordancy measure is as follows (Hosking and Wallis, 1997). With N the number of sites in a region, let

$$\mathrm{u}_i = \left[t^{(i)} t_3^{(i)} t_4^{(i)} \right]^{\mathrm{T}} \tag{5.10}$$

be a vector with t, t_3, and t_4 estimates for site i. The superscript T denotes the transposition of a vector or matrix. Let

$$\bar{\mathrm{u}} = N^{-1}\sum_{i=1}^{N}\mathrm{u}_i \tag{5.11}$$

be the group average. The matrix of sums of squares and cross-products is defined as

$$\mathrm{A} = \sum_{i=1}^{N}(\mathrm{u}_i - \bar{\mathrm{u}})(\mathrm{u}_i - \bar{\mathrm{u}})^{\mathrm{T}}. \tag{5.12}$$

The discordancy statistic for site i is then given by

$$D_i = \frac{1}{3}N(\mathrm{u}_i - \bar{\mathrm{u}})^{\mathrm{T}}\mathrm{A}^{-1}(\mathrm{u}_i - \bar{\mathrm{u}}). \tag{5.13}$$

For a region with 15 or more sites, site i is considered discordant if $D_i \geq 3$. For this study, all regions considered contained 15 or more sites. Hosking and Wallis (1997) note that the discordancy measure is an increasing function of the number of sites in a region because larger regions are more likely to contain sites with large values of D_i. However, Hosking and Wallis (1997) still recommend that $D_i \geq 3$ be considered discordant, since such sites have L-moment ratios that significantly differ from the regional average.

In addition to assisting in locating abnormalities in a data set, the discordancy measure can aid in identifying homogeneous regions. If a site is discordant in a particular region, it could be moved to another region. However, it is recognized that a site's L-moments may differ from other similar sites by chance alone. An example of this is the Beaverton Power Plant station, in which the largest 1-hour rainfall was recorded for the State (5.02 inches). For the State as one region, its discordancy measure (D_i) is 5.47. Because such an event is deemed to have an equal chance of occurring at any other site in the State, the site is kept as a member of the region.

Identifying Homogeneous Regions. The purpose of this step is to form groups of stations that satisfy the homogeneity condition, i.e., stations with frequency distributions that are identical apart from a station-specific scale factor. Stations can be grouped subjectively by site characteristics (i.e., latitude, longitude, elevation, and mean annual precipitation). For example, Schaefer (1990) defined homogeneous regions based on mean annual precipitation for a regional frequency analysis study of annual maximum precipitation in the State of Washington.

Stations can also be grouped objectively using cluster analysis procedures. Cluster analysis is a multivariate statistical analysis procedure for partitioning a data set into groups. The procedure involves assigning a data vector to each site. Sites are then divided into groups based on the similarity of their data vectors. The data vectors can consist of site statistics, site characteristics, or some combination of both. Hosking and Wallis (1997) recommend basing the regionalization of sites on site characteristics alone. This is because site characteristics are known quantities before any data are measured at the site. If site statistics were used, sites that have observed a large outlier, for example, could be grouped together, resulting in inaccurate quantile estimates for that region. Furthermore, the use of site characteristics for forming regions allows the use of site statistics to test the appropriateness of the grouped sites. Other studies implementing cluster analysis procedures based on site characteristics are described by Fovell and Fovell (1993), Hosking and Wallis (1996) and Bates et al., (1998).

To investigate the possibility of dividing the State into two or more homogeneous regions, cluster analysis was performed using latitude, longitude, elevation, and mean annual precipitation as the site characteristics. Clusters were formed using a computer

program developed by Hosking (1997). This program applies Ward's method, which tends to produce clusters containing the same number of sites. In Ward's method the distance between two clusters is the sum of squares of differences in common variables between the two clusters. The clusters formed using Ward's method are then redefined using a *K*-Means clustering algorithm (Hartigan and Wong, 1979). The aim of the algorithm is to search for a *K*-partition with locally optimal within-cluster sum of squares by moving sites from one cluster to another.

In order to test the appropriateness of a group of sites, Hosking and Wallis (1997) present a heterogeneity measure called the *H*-statistic. This statistic compares the between-site variation in sample *L*-moments for a group of sites with what would be expected for a homogeneous region (Hosking and Wallis, 1997). To determine what would be expected, repeated Monte Carlo simulations of a homogeneous region with sites having record lengths equal to those of the observed data are performed. From the simulated values the mean and standard deviation of the chosen dispersion measure are obtained. To compare the observed and simulated differences, the *H*-statistic is defined as (Hosking and Wallis, 1997):

$$H = \frac{(observed\ dispersion)\ -\ (mean\ of\ simulations)}{(standard\ deviation\ of\ simulations)}. \tag{5.14}$$

There are three measures of the *H*-statistic. The first, H(1), is the standard deviation, weighted according to record length, of the at-site *L*-CVs. This is deemed to be the most important because variation in the *L*-CV has a much larger effect than variation in the *L*-skewness or *L*-kurtosis on the accuracy of the final quantile estimates (Hosking and Wallis, 1997). The second measure, H(2), is the average distance from the

site coordinates to the regional average on a plot of *L*-CV vs. *L*-skewness. The third measure, H(3), is the average distance from the site coordinates to the regional average on a plot of *L*-skewness vs. *L*-kurtosis. A region is declared "acceptably homogeneous" if $H < 1$, "possibly heterogeneous" if $1 \leq H < 2$, and "definitely heterogeneous" if $H \geq 2$.

Choosing a Frequency Distribution. In regional frequency analysis, a single frequency distribution is fit to the data from several sites in a homogeneous region. Because the "true" distribution of rainfall is not known, a distribution must be chosen that not only provides a good fit to the data, but will also yield robust and accurate quantile estimates for each site in the region.

To determine an appropriate distribution for regional quantile estimation, Hosking and Wallis (1997) introduce another statistic called the *Z*-statistic. The *Z*-statistic, a goodness-of-fit measure for three-parameter distributions, measures how well the theoretical *L*-kurtosis of the fitted distribution matches the regional average *L*-kurtosis of the observed data. The *Z*-statistic for a particular distribution is defined as (Hosking and Wallis, 1997)

$$Z^{\mathrm{DIST}} = (\tau_4^{\mathrm{DIST}} - t_4^{\mathrm{R}} + B_4)/\sigma_4 , \tag{5.15}$$

where τ_4^{DIST} is the theoretical *L*-kurtosis for the candidate distribution, t_4^{R} is the regional average *L*-kurtosis weighted by record length, B_4 is a simulation-based value to correct for the bias associated with estimating t_4^{R}, and σ_4 is an estimate of the standard deviation of t_4^{R} obtained from repeated simulation of a homogeneous region whose sites have the candidate frequency distribution and identical record lengths as the observed data. The

fit of the distribution is declared satisfactory if $|Z^{DIST}| \leq 1.64$. This criterion corresponds to an acceptance of the hypothesized distribution at a confidence level of approximately 90% (Hosking and Wallis, 1997).

The candidate three-parameter distributions considered for quantile estimation for this study were the Generalized Logistic (GLO), the Generalized Extreme Value (GEV), the Lognormal (LN3), the Pearson Type III (PE3), and the Generalized Pareto (GPA). Two-parameter distributions were not considered because estimates of tail quantiles can be severely biased if the shape of the tail of the true frequency distribution is not well approximated by the fitted distribution. The use of a distribution with more parameters, when the parameters are estimated accurately, yields less biased estimates of quantiles in the tails of the distribution (Hosking and Wallis, 1997).

The Regional L-Moment Algorithm. To estimate a chosen distribution's parameters and obtain quantile estimates, the regional *L*-moment algorithm was used (Hosking and Wallis, 1997). This procedure involves fitting the chosen distribution using the method of *L*-moments; its parameters are estimated by equating the population *L*-moments of the distribution to the sample *L*-moments derived from the observed data. Next, sample *L*-moment ratios from each site in a homogeneous region are weighted according to record length and combined to give regional average *L*-moment ratios. Hosking and Wallis (1997) found that averaging *L*-moment ratios rather than the *L*-moments themselves yields more accurate quantile estimates in all cases examined. Next, the regional mean is set equal to 1, and regional quantile estimates are derived. Final quantile estimates are

obtained by multiplying the regional quantile estimate by the index flood, which for this study is the at-site estimate of the mean.

The formulation of the regional *L*-moment algorithm is as follows. Assume that there are *N* sites in a region, with site *i* having record length n_i, sample mean $\ell_1^{(i)}$, and sample *L*-moment ratios $t^{(i)}$, $t_3^{(i)}$, $t_4^{(i)}$, and $t_5^{(i)}$. The regional average *L*-moment ratios t^{R}, t_3^{R}, t_4^{R}, and t_5^{R}, are weighted according to record lengths as given by (Hosking and Wallis, 1997):

$$t^{\mathrm{R}} = \sum_{i=1}^{N} n_i t^{(i)} \Big/ \sum_{i=1}^{N} n_i \,, \tag{5.16}$$

$$t_r^{\mathrm{R}} = \sum_{i=1}^{N} n_i t_r^{(i)} \Big/ \sum_{i=1}^{N} n_i \,, \qquad r = 3, 4, 5. \tag{5.17}$$

Next, the regional average mean is set to 1:

$$\ell_1^{\mathrm{R}} = 1. \tag{5.18}$$

Let $\hat{q}(.)$ be the quantile function of the fitted regional frequency distribution, and let $\ell_1^{(i)}$ be the index flood, or the sample mean of the at-site data. The quantile estimate at site *i* for nonexceedance probability *F* (i.e., 1-1/*T*) is given by (Hosking and Wallis, 1997):

$$\hat{Q}_i(F) = \ell_1^{(i)} \hat{q}(F). \tag{5.19}$$

5.6 Determination of Rainfall IDF Estimates at Ungaged Sites

To obtain rainfall IDF estimates at ungaged sites, the regional quantile estimates derived from data at gaged sites within a region are interpolated to all ungaged sites in that region. Specifically, the index flood, or the at-site mean values, are spatially interpolated over the State using geostatistical methods. This allows for rainfall IDF estimates for durations of 1, 2, 3, 6, 12, 18 and 24 hours to be determined for any location in the State of Michigan. For durations of less than 1 hour, a procedure was devised to extrapolate the results obtained for the SEMCOG gages. The procedure assumes that the ratio of *N*-minute to 60-minute rainfall intensity is constant throughout the state. Then, based on the estimate of *N*-minute rainfall intensity for a given return period in the Detroit area, an estimate of *N*-minute rainfall intensity for the same return period at another location can be estimated as:

$$Q_i^N = Q_D^N \left(\frac{Q_i^{60}}{Q_D^{60}} \right) \tag{5.20}$$

where

Q_i^N = *N*-minute rainfall intensity at site *i*

Q_D^N = *N*-minute rainfall intensity in the Detroit area

Q_i^{60} = 60-minute rainfall intensity at site *i*

Q_D^{60} = 60-minute rainfall intensity in the Detroit area

5.7 The Partial Duration Series Model

The formulation presented in this section is for a partial duration series (PDS) model based on the index flood regional frequency analysis procedure outlined by Hosking and Wallis (1997). A PDS, or peaks over a threshold (POT) series, includes all values above a truncation level or threshold. This model assumes that all values above a threshold are Generalized Pareto (GPA) distributed, which suggests the annual maximum values to be Generalized Extreme Value (GEV) distributed (Hosking and Wallis, 1987; Stedinger et al., 1993; and Madsen et al., 1997). Thus, the model introduced herein is similar to the AMS/GEV model presented in the next section. Along with these theoretical reasons for using the GPA distribution, the GPA distribution has been determined to provide the best fit to the PDS data empirically, as shown in Chapter 6.

It is generally assumed in a PDS analysis that the arrival of peaks is described by a Poisson process. That is, $N(t)$, the number of exceedances in t years, is Poisson distributed with probability function (Madsen and Rosbjerg, 1997)

$$P\{N(t)=n\}=\frac{(\lambda t)^n}{n!}\exp(-\lambda t) \qquad n=0,1,2,\ldots \tag{5.21}$$

where the Poisson parameter λ equals the expected number of exceedances per year. It is also assumed that the rainfall magnitudes above the threshold are independent and identically distributed following the GPA distribution. Criteria for independence of events are discussed in Chapter 3.

Because more than one event can occur in a year in a PDS, the recurrence interval of a given rainfall event estimated using the PDS, T_p, will be less than the recurrence

interval estimated using the AMS, T_a (denoted T elsewhere in this document). This relationship is given by (Stedinger et al., 1993)

$$T_p = -\frac{1}{\ln\left(1 - 1/T_a\right)}. \tag{5.22}$$

Analogous to the relationship in Equation 5.22, Rosbjerg (1985) has shown the T-year event quantile (F) in the distribution of exceedances to be defined as

$$F = 1 - \frac{1}{\hat{\lambda}T} \tag{5.23}$$

where $\hat{\lambda}$ is an estimator of the Poisson parameter, which is defined as (Madsen and Rosbjerg, 1997)

$$\hat{\lambda} = \frac{N}{t}. \tag{5.24}$$

Madsen and Rosbjerg (1997) present a PDS/GPA index flood model for modeling the excesses over a threshold. The series of excess values is given by $X_i = Q_i - q_0$, where Q_i is the measured rainfall magnitude and q_0 is the threshold. This model requires that the index flood parameters, which are the mean and the Poisson parameter, be estimated from at-site data. In this model, the T-year event estimator for a given site i is (Madsen et al., 1997)

$$\hat{Q}_i(T) = q_0 + \ell_1^i \frac{1 + \hat{\kappa}^{\mathrm{R}}}{\hat{\kappa}^{\mathrm{R}}} \left[1 - \left(\frac{1}{\hat{\lambda}_i T} \right)^{\hat{\kappa}^{\mathrm{R}}} \right] \tag{5.25}$$

where $\hat{\kappa}^{\mathrm{R}}$ is an estimate of the regional GPA shape parameter, and q_0 is the regional threshold (or location parameter ξ of the GPA distribution). Because the threshold q_0 is

assumed to be known, the regional shape parameter is derived from the regional estimate of the L-CV. Madsen et al. (1998) have successfully applied this model to derive rainfall IDF estimates for Denmark.

Determination of the threshold q_0 is a topic seldom discussed in the literature. The PDS/GPA model presented by Madsen and Rosbjerg (1997) requires that a regional threshold be determined, i.e., that the threshold be the same at all sites. Madsen and Rosbjerg (1997) recommend a procedure based on a frequency factor k:

$$q_0 = E\{Q\} + kS\{Q\} \tag{5.26}$$

where $E\{Q\}$ and $S\{Q\}$ are, respectively, the expected mean and the expected standard deviation of a series of daily or hourly data. Values of k ranging from 3 to 3.5 have been found to be appropriate (Madsen and Rosbjerg, 1997).

Because all of the PDS data for this study have been compiled with $\hat{\lambda} = 2$ (i.e., a station's PDS contains twice the number of peaks as its corresponding AMS), the "true" threshold of each PDS is not known. Thus, a regional threshold cannot reasonably be determined. This means the model presented above (Madsen and Rosbjerg, 1997), which requires a regional threshold and an at-site estimate of $\hat{\lambda}$, cannot be applied directly. Additionally, such a model would complicate the procedure for estimating IDF values at ungaged sites, since two parameters would vary across the State.

Since a fixed number of peaks was used to define the PDS, the formulation of the PDS changes because the threshold is now a stochastic variable. This requires the threshold (or location parameter of the GPA distribution) to be estimated from the data. This estimate of the GPA location parameter $\hat{\xi}^{\mathrm{R}}$ is (Hosking and Wallis, 1997)

$$\hat{\xi}^{\mathrm{R}} = \ell_1^{\mathrm{R}} - \left(2 + \hat{\kappa}^{\mathrm{R}}\right)\ell_2^{\mathrm{R}} \tag{5.27}$$

where ℓ_1^{R} is equal to 1, ℓ_2^{R} is the regional estimate of the scale, and $\hat{\kappa}^{\mathrm{R}}$ is the regional estimate of the GPA shape parameter given by (Hosking and Wallis, 1997)

$$\hat{\kappa}^{\mathrm{R}} = (1 - 3t_3^{\mathrm{R}})/(1 + t_3^{\mathrm{R}}). \tag{5.28}$$

The estimate of the GPA scale parameter $\hat{\alpha}^{\mathrm{R}}$ is given by (Hosking and Wallis, 1997)

$$\hat{\alpha}^{\mathrm{R}} = (1 + \hat{\kappa}^{\mathrm{R}})(2 + \hat{\kappa}^{\mathrm{R}})\ell_2^{\mathrm{R}}. \tag{5.29}$$

For $\kappa \neq 0$, the quantile function of the fitted regional GPA distribution is then

$$\hat{q}(T) = \hat{\xi}^{\mathrm{R}} + \frac{\hat{\alpha}^{\mathrm{R}}}{\hat{\kappa}^{\mathrm{R}}}\left[1 - \left(\frac{1}{\hat{\lambda}^{\mathrm{R}} T}\right)^{\hat{\kappa}^{\mathrm{R}}}\right]. \tag{5.30}$$

If $\kappa = 0$, the exponential distribution results, and the quantile function is given by (Hosking and Wallis, 1997)

$$\hat{q}(T) = \hat{\xi}^{\mathrm{R}} - \hat{\alpha}^{\mathrm{R}} \ln\left(\frac{1}{\hat{\lambda}^{\mathrm{R}} T}\right). \tag{5.31}$$

The quantile estimate at site *i* for the regional *T*-year event is

$$\hat{Q}_i(T) = \ell_1^{(i)}\hat{q}(T). \tag{5.32}$$

Using this formulation, the mean is still inferred from at-site data, but $\hat{\lambda}^{\mathrm{R}}$ is estimated regionally. This formulation will be used to obtain rainfall IDF estimates using PDS data for this study.

Because of the procedure used to compile the PDS for this study, $\hat{\lambda}^{\mathrm{R}}$ is restricted to values less than or equal to 2. The choice of $\hat{\lambda}^{\mathrm{R}}$ is important because it has an effect

on the final quantile estimates. Tavares and Da Silva (1983) showed that estimates from a PDS have less variance than those from an AMS if $\lambda > 2$. Madsen et al. (1997), using Monte Carlo simulation, have shown for certain values of λ that the performance of their PDS/GPA model equals that of the AMS/GEV model (to be presented in the next section). The results from their investigation are shown in Table 5.1 (Madsen et al., 1997). For values of the shape parameter ranging from –0.2 to –0.1, which is the case for the PDS data in Michigan, λ values range from 2.2 to 4.07 for different record lengths and recurrence intervals. Madsen et al. (1997) also found the PDS/GPA model to be more efficient for larger values of λ. Furthermore, in a PDS analysis updating rainfall IDF estimates for Denmark, Madsen et al. (1998) used $\hat{\lambda}$ values that ranged from 2.5-3.2.

In light of these findings and the notion that a larger $\hat{\lambda}^{R}$ contains more peaks and will thus provide a better fit to the GPA distribution, all data provided by the State Climatologist ($\hat{\lambda}^{R} = 2$) were used to develop rainfall IDF estimates for this study.

Table 5.1. Mean annual number of exceedances in PDS (λ) to obtain equal performance of PDS/GPA and AMS/GEV regional *T*-year event estimators in homogeneous regions with different shape parameters κ (Madsen et al., 1997).

	$T = 10$		$T = 100$				$T = 1000$	
κ	$t = 30$	$t = \infty$	$t = 10$	$t = 30$	$t = 50$	$t = \infty$	$t = 30$	$t = \infty$
-0.3	1.6	1.67	2.2	2.1	2.1	2.13	2.0	2.25
-0.2	2.2	2.20	2.8	2.7	2.7	2.84	2.5	3.06
-0.1	2.8	2.83	3.7	3.6	3.6	3.73	3.3	4.07
0.0	3.7	3.59	4.9	4.8	4.8	4.80	4.4	5.29
0.1	4.8	4.59	6.6	6.6	6.7	6.14	6.1	6.77
0.2	7.6	6.31	9.7	10.0	10.0	8.22	9.3	8.96
0.3	18.5	11.3	17.7	20.0	20.6	13.1	16.5	13.6

Results are obtained from simulations (t (record length) = 10, 30, 50 years) for a region of $M = 20$ sites and from asymptotic theory ($t = \infty$) corresponding to $M \rightarrow \infty$.

A useful application of this model is that the AMS distribution corresponding to the parent PDS/GPA model is a GEV distribution with the same shape parameter as the GPA distribution. For the AMS greater than q_0, the cdf of this GEV distribution is (Stedinger et al., 1993)

$$F(q) = \exp\left[-\left(1-\kappa\frac{q-\xi}{\alpha^*}\right)^{1/\kappa}\right] \qquad \kappa \neq 0. \tag{5.33}$$

$$F(q) = \exp\left[-\left(\frac{q-\xi}{\alpha}\right)\right] \qquad \kappa = 0 \tag{5.34}$$

For $q \geq q_0$, the transformed parameters ξ and α^* are given by (Stedinger et al., 1993)

$$\xi = q_0 + \frac{\alpha}{\kappa}\left(1-\lambda^{-\kappa}\right) \qquad \alpha^* = \alpha\lambda^{-\kappa} \qquad \kappa \neq 0 \tag{5.35}$$

$$\xi = q_0 + \alpha\ln(\lambda) \qquad \kappa = 0 \tag{5.36}$$

where estimates of α and κ are both derived from PDS data. The AMS distribution derived from the PDS/GPA model is valid only for $q > q_0$. Because nothing is known about the AMS distribution below q_0, it is not applied in practice. The complete AMS/GEV model that is applied in practice is presented in the next section.

5.8 The Annual Maximum Series Model

Unlike the PDS/GPA model, the AMS/GEV model has been frequently explored and has found wide application in frequency analysis studies (e.g., Hosking et al., 1985; Schaefer, 1990; Julian et al., 1999; and Loucks et al., 2000). This model, also based on the procedure outlined by Hosking and Wallis (1997), assumes that annual maximum rainfall magnitudes are independently and identically distributed following the GEV

distribution. Of all the candidate distributions considered, the GEV distribution was deemed to provide the best fit to the AMS data, as discussed in Chapter 6.

Like the GPA distribution, the GEV distribution has three parameters to be estimated from regional data. The regional *L*-moment estimate of the shape parameter, κ is (Hosking et al., 1985)

$$\hat{\kappa}^{\mathrm{R}} \approx 7.8590c^{\mathrm{R}} + 2.9554\left(c^{\mathrm{R}}\right)^2, \qquad c^{\mathrm{R}} = \frac{2}{3+t_3^{\mathrm{R}}} - \frac{\ln(2)}{\ln(3)} \tag{5.37}$$

where t_3^{R} is the regional estimate of the *L*-skewness. Estimates of the GEV distribution scale parameter α and the location parameter ξ are given by (Hosking et al., 1985)

$$\hat{\alpha}^{\mathrm{R}} = \frac{\ell_2^{\mathrm{R}}\hat{\kappa}^{\mathrm{R}}}{(1-2^{-\hat{\kappa}^{\mathrm{R}}})\Gamma(1+\hat{\kappa}^{\mathrm{R}})} \tag{5.38}$$

$$\hat{\xi}^{\mathrm{R}} = \ell_1^{\mathrm{R}} - \frac{\hat{\alpha}^{\mathrm{R}}}{\hat{\kappa}^{\mathrm{R}}}\left\{1-\Gamma(1+\hat{\kappa}^{\mathrm{R}})\right\} \tag{5.39}$$

where ℓ_2^{R} is the regional estimate of the scale, ℓ_1^{R} is the regional mean (set equal to 1), and $\Gamma(\ )$ denotes the gamma function.

For $\kappa \neq 0$, the quantile function of the fitted regional GEV distribution is then (Hosking and Wallis, 1997)

$$\hat{q}(T) = \hat{\xi}^{\mathrm{R}} + \frac{\hat{\alpha}^{\mathrm{R}}}{\hat{\kappa}^{\mathrm{R}}}\left[1-\left(-\ln\left(1-\frac{1}{T}\right)\right)^{\hat{\kappa}^{\mathrm{R}}}\right] \tag{5.40}$$

For $\kappa = 0$, the Gumbel distribution results, and the quantile function is given by (Hosking and Wallis, 1997)

$$\hat{q}(T) = \hat{\xi}^{\mathrm{R}} - \hat{\alpha}^{\mathrm{R}} \ln\left(-\ln\left(1 - \frac{1}{T}\right)\right). \tag{5.41}$$

Using the at-site mean as the index flood parameter, the regional T-year estimate for site i is (Hosking and Wallis, 1997)

$$\hat{Q}_i(T) = \ell_1^{(i)} \hat{q}(T). \tag{5.42}$$

5.9 Adjusting for Trends in Michigan Rainfall Data

Because a positive trend was detected in the daily AMS data, as shown in Chapter 4, a procedure for placing greater weight on recent data, while still incorporating data from the full period of record, has been developed. The procedure is similar to that proposed by Huff and Angel (1989). The regional quantile estimates are estimated using data from the entire period of record. However, the index flood values (at-site means) are derived from 1949-96 data only. This method incorporates observations from the entire period of record, but puts greater weight on those that have been observed in the last 48 years. It should be noted that only the estimates for the AMS 24-hour duration have been derived in this manner.

6.0 SPATIAL INTERPOLATION METHODS

6.1 Overview

For areas where no precipitation data exist (*i.e.*, ungaged sites), spatial interpolation methods can be applied to point rainfall IDF estimates to obtain interpolated estimates over a continuous area. The process of spatial interpolation can be achieved by fitting a surface to the point rainfall IDF estimates. Such interpolated rainfall IDF estimates are commonly presented as isopluvial maps. Figure 6.1 illustrates an isopluvial map of the 25-year, 1-hour rainfall intensity for the continental United States.

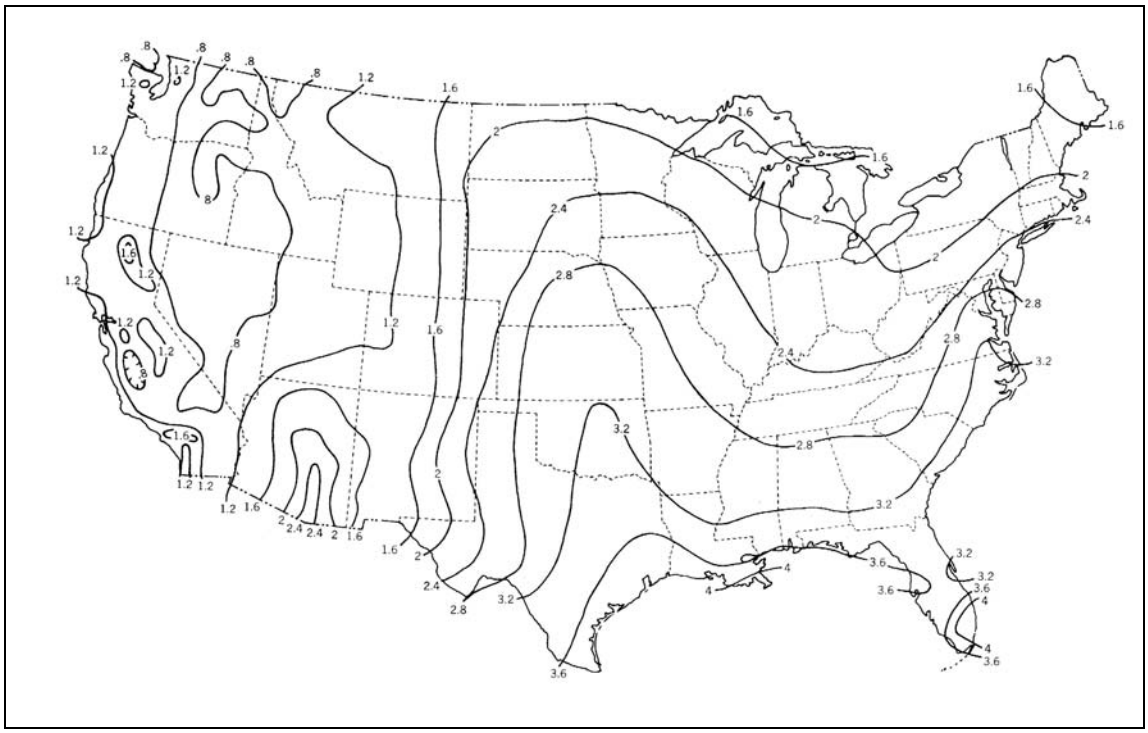

Figure 6.1. Isopluvial map illustrating the 25-year, 1-hour rainfall intensity for the continental United States.

Difficulty in selecting an appropriate spatial interpolation method can be attributed to sampling variability and sparsity of sample points, leading to a high degree

of uncertainty in frequency analysis estimates. To assist in accurately interpolating over a continuous area, regional information, such as distance from lake, elevation, or mean annual precipitation, may be used to increase confidence in the interpolated estimates.

As described in previous chapters, the regional frequency analysis algorithm applied in this study (Hosking and Wallis 1997) involves the identification of homogeneous regions, where clustering may be based on site characteristics such as geographical location, elevation, and other physical properties. After identification of homogeneous regions, a three-parameter distribution is selected using a goodness-of-fit test, and this distribution is then fitted to the data series to yield robust frequency-specific quantile estimates for each region. Two of the distribution parameters (e.g., the standard deviation and skew) are based on regional data and are assumed constant throughout the region, while the third distibution parameter (e.g., the mean) is site-specific and subject to sampling variability, therefore requiring spatial interpolation in order to derive isopluvial maps. Following spatial interpolation, the site-specific distribution parameter is multiplied by the frequency-specific quantile estimates for each region, resulting in regional IDF estimates.

This chapter focuses on the evaluation and selection of appropriate spatial interpolation techniques for generating isopluvial maps and determining rainfall IDF estimates at ungaged sites. Techniques described in some of the early documentation of rainfall IDF studies are investigated, as are more recently developed interpolation methods. In addition, this chapter outlines the ordinary kriging algorithm chosen to derive the new MDOT rainfall IDF estimates.

6.2 Previous Rainfall Frequency Studies

Early frequency analysis studies ignored the spatial distribution of rainfall by assuming the areas of interest were small enough that point representations were sufficiently representative of the regional variation in rainfall IDF estimates (Maidment 1993). As understanding of orographic effects improved, this assumption was no longer acceptable in frequency analysis studies.

With increasing availability of rainfall data and the advent of digital computers, spatial interpolation methods became useful tools for modeling regional variation in IDF estimates. In 1961, the National Weather Service (NWS, then the U.S. Weather Bureau) published Technical Paper 40 (Hershfield 1961) illustrating the development of forty-nine isopluvial maps for the continental U.S. for the 1- to 100-year recurrence intervals and 30-minute to 24-hour durations. Mathematical relationships consisting of ratio constants, frequency and duration variables were derived allowing for the computation of intensities for selected recurrence intervals and durations. By smoothing the data, the 2-year, 1-hour and 24-hour isopluvial patterns were delineated. The smoothing process consisted of drawing isolines between point values so that the standard deviation of the estimates was approximately equal in respect to sampling and other errors in the data and methods of analysis. To mask out local variation inherent in station-to-station estimates, 100-year to 2-year ratios for the 1- and 24-hour durations were plotted on a 3500-point grid and used to construct the 100-year, 1-hour and 24-hour maps. The remaining forty-five isopluvial maps were constructed by utilizing a computer program to plot a 3500-point grid for each duration-recurrence interval combination.

Out of growing environmental awareness during the 1970s, there came about an increase in demand for hydrologic planning and design for small drainage areas having very short times of concentration. In response to this demand, the National Oceanic and Atmospheric Administration (NOAA) was charged with updating Hershfield's (1961) 5- to 60-minute rainfall IDF estimates. Since it was found that orographic effects had a greater significant influence in the eleven westernmost states of the continental U.S., separate studies were performed for the eastern and western states. These were published as NOAA Atlas II (Miller et al. 1973) and NOAA Atlas I (Fredrick et al. 1977), respectively.

In NOAA Atlas I (Fredrick et al. 1977), 6 isopluvial maps were developed for 2- and 100-year recurrence intervals at 5-, 15-, and 60-minute durations for thirty-seven states from North Dakota to Texas and eastward. In addition, mathematical relationships for both recurrence interval and duration were derived to interpolate values for recurrence intervals between 2 and 100 years. Fredrick et al. (1977) elected to use an approach similar to Hershfield (1961) to develop ratio constants, however, they observed the ratios varied with both geography and frequency. To minimize the variation in the ratios, Fredrick et al. (1977) constructed six isopluvial maps and derived specific ratios for intermediate recurrence intervals and durations between the constructed maps. The 2-year, 60-minute isopluvial patterns were first constructed using a computerized space-averaging (or smoothing) technique and then used for guidance in the directional placement of isopluvial patterns for the remaining five maps. The space-averaging technique divided the study area into 0.5° latitude x 0.5° longitude rectangular grids and performed the following steps: 1) computed grid point averages using distance weighted

average of the stations' values within latitude-longitude grids; 2) applied a double linear interpolation function to estimate new station values and computed the difference in original station values and interpolated values; and 3) adjusted grid point estimates computed in step 1 by the average of the differences computed in step 2 and weighted by the distance function. The analyst repeated steps 2 and 3 until a desired degree of smoothing was achieved.

As understanding of hydrometeorological processes improved and more precipitation data became available through more extensive gage networks and longer gage records, it was determined that the earlier studies (Hershfield 1961; Miller et al. 1973; and Fredrick 1977) no longer presented the spatial resolution needed for certain areas of the country. As a result, several state highway departments and water resource agencies conducted independent frequency analysis studies to estimate local rainfall variations more accurately.

In 1986, Dunn (1986) constructed five rainfall IDF curves illustrating 2- to 100-year recurrence intervals and 5-minute to 24-hour durations for the Pennsylvania Department of Transportation. Five "regions of similar rainfall intensities" for Pennsylvania were delineated using four storm distributions, *i.e.*, 2- and 100-year recurrence intervals of 1- and 24-hour durations. The selection of the four storm distributions was based on their wide variation in both recurrence interval and duration, which enveloped the required recurrence intervals and durations for the study. Individual rainfall intensities for the four storms were constructed. Based on the maximum and minimum records in the four storm distributions combined, a classification scheme was developed which divided intensities into five percentiles. After plotting the percent

magnitudes for each storm distribution, the four maps were overlaid and boundaries of similar rainfall intensities were drawn. Orographic features and "peculiar histories" (such as floods affecting Johnstown, PA) were considered in the final location of the five regions.

By the late 1980s, the State of Illinois was motivated to revise IDF estimates due to increased flooding in northern Illinois and a study showing apparent climatic trends influencing frequency distributions of heavy rainstorms in Illinois from 1901-1980 (Angel and Huff 1997). In addition, Illinois' IDF estimates had not been updated since Hershfield's (1961) work (Huff and Angel 1989). In 1989, the Illinois State Water Survey Division published Bulletin 70 (Huff and Angel 1989), which updated rainfall IDF estimates by dividing the state into ten "approximately homogeneous" climatic sections based on assessment of gage data with consideration of meteorological and climatological information. For each climatic division, Huff and Angel (1989) presented the updated estimates in tabular and graphical (*i.e.*, IDF curves) forms. In addition, forty-eight isopluvial maps were developed for the 2- to 100-year recurrence intervals and 1- to 72-hour durations. Documentation on the development of the isopluvial maps provided little information on the methodology used except that a combination of statistical techniques, guided by available meteorological and climatological knowledge, was used. In 1992, the Illinois State Water Survey Division published Bulletin 71 (Huff and Angel 1992) which updated rainfall IDF estimates for nine Midwest states (*i.e.*, Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Missouri, Ohio, and Wisconsin) using similar procedures used in the Huff and Angel (1989) study.

In 1990, the Michigan Department of Natural Resources revised the rainfall IDF estimates for the state of Michigan and presented the estimates as six isopluvial maps for 2- to 100-year recurrence intervals at the 24-hour duration (Sorrel and Hamilton 1990). Very little documentation was provided on the methods used to construct the isopluvial maps, except that a commercial plotting package was used to plot and contour rainfall intensities, and minor irregularities were hand-adjusted.

Current MDOT rainfall IDF estimates are a compilation of results from three rainfall frequency studies (U.S. Weather Bureau 1955; Hershfield 1961; Sorrell and Hamilton 1990) (Michigan Department of Transportation 1996). As part of the *Michigan Road Design Manual*, the state of Michigan was divided into four-rainfall frequency zones (Michigan Department of Transportation 1996). For each zone, rainfall IDF estimates are presented in tabular form for the 10- and 50-year recurrence intervals and 10- to 240-minute durations. No documentation was found on the methods used in delineating the four frequency zones or compiling the IDF estimates.

Throughout the literature on frequency analysis studies, several interpolation techniques have been employed to generate isopluvial maps from point IDF estimates. Additionally, every study has incorporated some degree of smoothing to address sampling variability (estimation error). However, these interpolation and smoothing techniques have been highly subjective, requiring interaction with the analyst and relying on expert knowledge and judgement. Subjective approaches make peer review difficult and acceptance of the final results may be heavily based on the professional reputation of the analyst. Objective mapping techniques, on the other hand, are reproducible and more amenable to peer review.

6.3 Assessment of Spatial Interpolation Algorithms

A goal of this study is to use the most objective techniques available for spatial interpolation of site-specific parameters in a regional analysis, while recognizing that some engineering judgement will still be required. This section assesses the appropriateness in spatially interpolating point IDF estimates of several spatial interpolation algorithms. Although there are many spatial interpolation algorithms available (Lancaster and Salkauskas 1986; Watson 1992), the review will be limited to commonly used spatial interpolation methods, such as those available in a commercial geostatistical software package or GIS. Specifically, the assessment will focus on the strengths and weaknesses of the trend surface analysis, thin-plate splines, inverse distance weighting, and kriging (ordinary, universal, and co-kriging) algorithms in developing isopluvial maps.

6.3.1 Trend Surface Analysis

The trend surface analysis algorithm simply uses multiple regression (*i.e.*, least squares) to fit a polynomial surface to the entire set of observations. Since final interpolated surfaces represent the broad regional trend in the variation implied by the data, and seldom pass exactly through the original data points, the algorithm is typically referred to as an inexact interpolator Figure 6.2 illustrates an example of a trend surface of preliminary 2-year, 1-hour rainfall intensity estimates for Michigan in the y-z plane. Comparing the point rainfall intensity estimates with the fitted curve illustrates the high spatial variability and the degree of smoothing that is incorporated into the final interpolated surface.

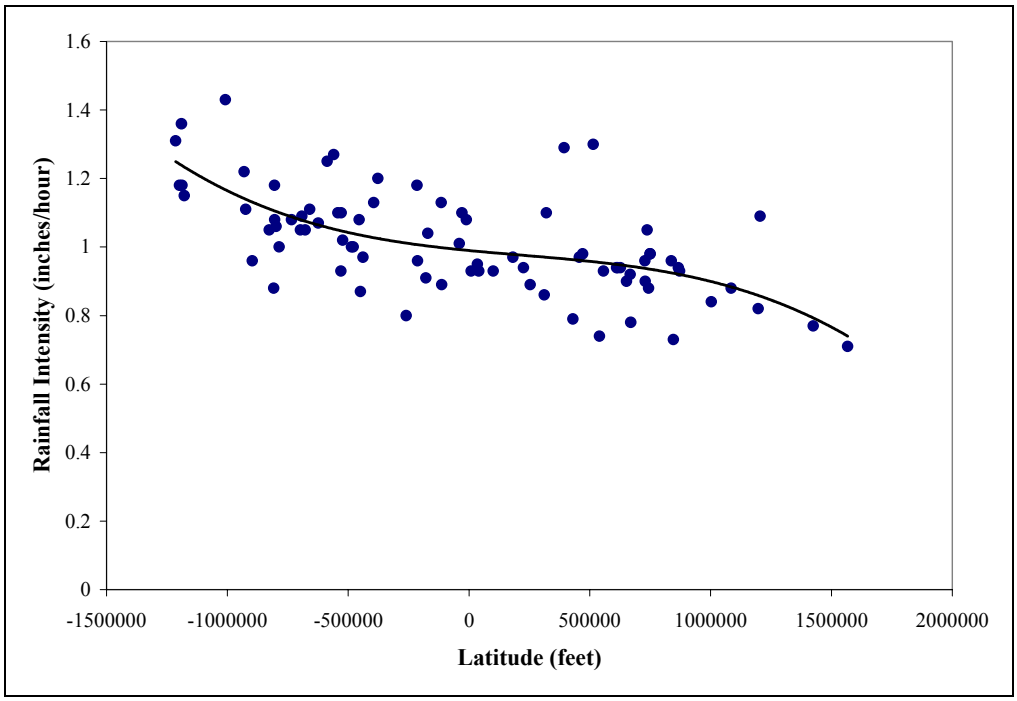

Figure 6.2. An example of a trend surface of preliminary 2-year, 1-hour rainfall intensity estimates for Michigan in the y-z plane.

The trend surface analysis algorithm assumes the following: 1) the geographical coordinates are the independent variables, and the attribute to be predicted (in this case, rainfall intensity) is the dependent variable; 2) regression errors are independent of location; and 3) the data are normally distributed (Burrough and McDonnell 1998). Advantages of using trend surface analysis for developing isopluvial maps are that the interpolated surface behaves conservatively between observations and local variations are dismissed as random, unstructured noise (Watson 1992; Burrough and McDonnell 1998). A disadvantage of using trend surface analysis is that the estimated surface is susceptible to outliers in the data and edge effects, and the surface must follow a polynomial function. Furthermore, error assessment is limited to goodness-of-fit and analysis of variance (ANOVA) techniques (Burrough and McDonnell 1998). These techniques

usually assume that rainfall IDF estimates are normally distributed, which is typically not the case.

6.3.2 Thin-plate Splines

Thin-plate splines also use multiple regression to fit a polynomial surface to a set of observations. However, the algorithm performs piece-wise multiple regression on subsets of observations that are within a predefined neighborhood, which allows local variation in the observations to be retained in the final interpolated surface. Figure 6.3 illustrates an one-dimensional view of piece-wise polynomial regression using thin-plate splines on a sub-set of 2-year, 1-hour rainfall intensity estimates. Through piece-wise polynomial regression, all of the spatial variability is incorporated into the final interpolated surface.

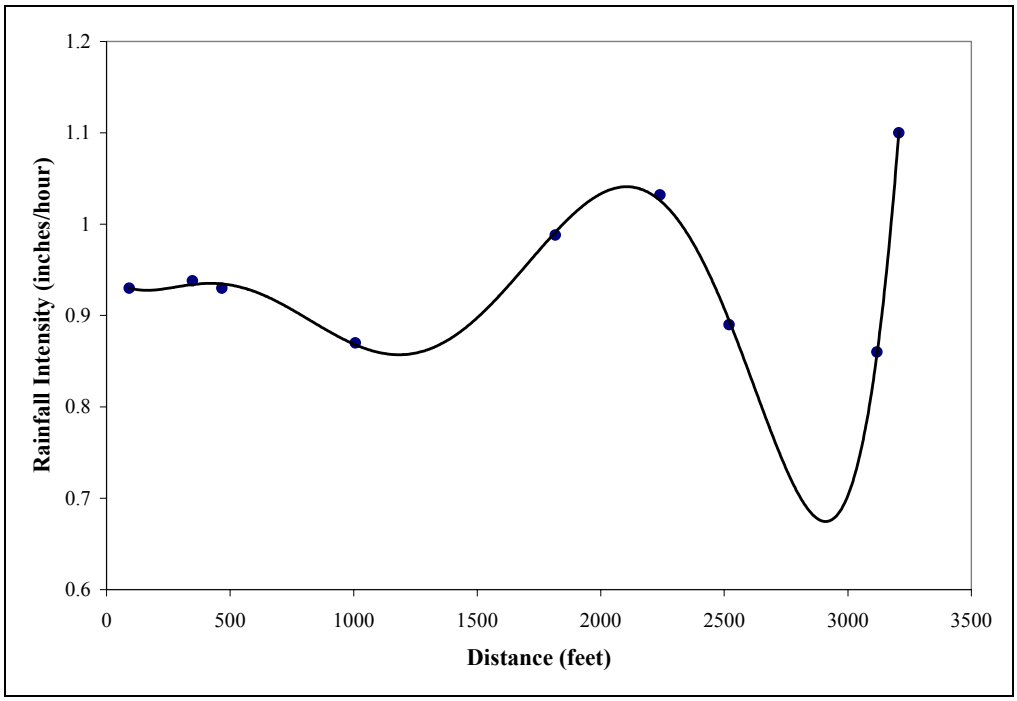

Figure 6.3. Cross-section of a piece-wise multiple regression using thin-plate splines on a subset of 2-year, 1-hour rainfall intensity estimates defined by a pre-defined neighborhood.

Splines follow the general notion that interpolated values are similar to the nearest known observation values. The algorithm imposes the following two conditions: 1) the surface must pass exactly through observation points, and 2) the surface must have minimum curvature, *i.e.*, the least possible change in slope, at each observation point. The advantage of using thin-plate splines with respect to rainfall IDF estimates is that only observations within a predefined vicinity influence interpolated values. The disadvantages of thin-plate splines are that there is no method for selecting an appropriate neighborhood radius size, and there is no direct method for assessing the error in interpolated values. Also, interpolated surfaces may contain unrealistic highs and lows as a result of exact interpolation (Burrough and McDonnell 1998), as apparent in Figure 6.3 at a distance of approximately 2900 feet.

6.3.3 Inverse Distance Weighting

Similar to thin-plate splines, inverse distance weighting follows the principle that nearby observation points are more influential than distant observations. The inverse distance weighting algorithm involves the following steps: 1) select the nearest observation points within a predefined neighborhood; 2) assign a weight to each observation based on its distance from the interpolation point; 3) sum the weighted observations to determine an average. Weights are assigned for each observation point within the search neighborhood using Equation 6.1 (Watson 1992):

$$w_i = \frac{d_i^{-p}}{\sum_{j=1}^{N} d_i^{-p}} \tag{6.1}$$

where w_i is the weight assign to the ith observation point, d_i is the distance to the ith observation point from the interpolation point, and p is an arbitrary power of distance, which influences how the interpolated surface behaves between points (Watson 1992). Due to the mathematical nature of inverse distance weighting, the algorithm is an exact interpolator, as shown in Equation 6.1 (at an observation point location, the weight tends to infinity). The advantages of using inverse distance weighting for isopluvial maps are that the interpolated surface is confined within the range of the point values, and only observations within a predefined vicinity influence the interpolated estimates. Disadvantages of the algorithm are that there are no methods of testing the quality of predictions, the final interpolated surface is strongly dependent on the size of the neighborhood radius and dominated by local variation, and the surface slope may be discontinuous at observation points as a result of exact interpolation.

6.3.4 Kriging

Kriging is the geostatistical method of interpolation that provides the best, *i.e.*, minimum variance, unbiased linear estimates of the value of a parameter at unmeasured locations from a set of observations. Similar to inverse distance weighting, the kriging algorithm models spatial variation by assigning weights to the observations within a predefined search neighborhood, as shown in Equation 6.2 (Burrough and McDonnell 1998).

$$\hat{z}(x_0) = \sum_{i=1}^{n} \lambda_i \cdot z(x_i) \tag{6.2}$$

where x_i are measured (observed) values; λ_i are assigned weights, where $\sum_{i=1}^{n} \lambda_i = 1$ so that the estimate is unbiased; and $\hat{z}(x_0)$ is the value to be estimated at location x_0. However, unlike the previously discussed algorithms, kriging also provides a theoretical basis for determining the most appropriate weights and size of the search neighborhood. Kriging optimizes spatial interpolation based on the assumption that spatial variation consists of three major components: 1) a structural component, having a constant mean or trend; 2) a random, but spatially correlated component; and 3) a spatially uncorrelated component (random noise or residual error) (Burrough and McDonnell 1998). This treatment of the variation is known as the regionalized variable theory, which is based on the intrinsic hypothesis that assumes once structural effects have been accounted for, the remaining variation is homogeneous, *i.e.*, differences between sites are only a function of distance (Armstrong 1998). Although there are several variations of kriging, only ordinary kriging, universal kriging, and co-kriging will be assessed for use in this study to develop isopluvial maps.

Ordinary kriging provides a means of interactively investigating the spatial variation of the data, which allows for the selection of the best estimation method prior to generating the final interpolated surface. This process involves computing the experimental semivariogram and fitting to it a suitable semivariogram model. Common semivariogram models are the spherical, circular, exponential, Gaussian, and linear models (Armstrong 1998; Watson 1992). Estimating parameters of the semivariogram model (lag distance, nugget, range, and sill) acts as a surrogate for identifying appropriate interpolation control parameters, such as the size of the search neighborhood and the necessary weighting. Figure 6.4 illustrates a theoretical semivariogram model fitted to an experimental semivariogram with several model parameters labeled.

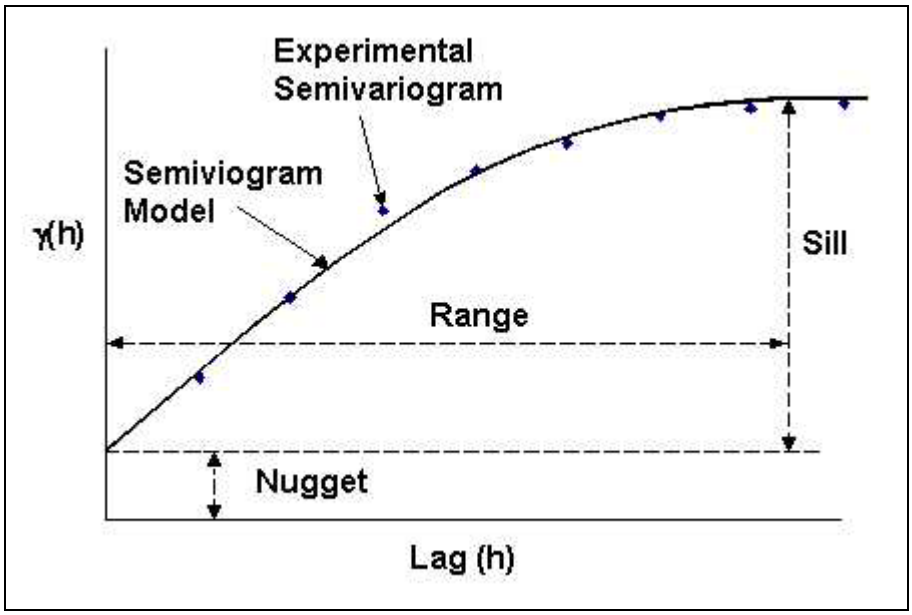

Figure 6.4. An example of a semivariogram model fitted to the experimental semivariogram, with identification of the nugget, range, and sill.

The presence of a nugget signifies variation due to measurement error or uncorrelated, unstructured noise. The range represents the distance beyond which

observations have no influence on the interpolated estimate. For most semivariogram models, the range is identified as the distance at which the semivariance levels off (at the value of the sill). Just as bin size is used in constructing histograms, the lag distance is the separation distance between points for which the squared difference (*i.e.*, the covariance) in the attribute being interpolated is averaged and plotted as part of the experimental semivariogram.

Advantages of using ordinary kriging for mapping rainfall IDF estimates are that the use of a semivariogram model assists in the selection of appropriate interpolation control parameters, and the algorithm provides a direct estimate of the quality of the interpolated surface in terms of the estimation variance. Disadvantages of ordinary kriging are that the selection of the appropriate semivariogram model and lag distance introduces some degree of subjectivity and requires knowledge of geostatistical theory.

Universal kriging combines the theories of trend surface analysis and ordinary kriging and is used when a known trend exists in the data (Burrough and McDonnell 1998). Trend surface analysis is first performed on the data to remove the existing trend. Ordinary kriging is then performed on the residuals of the trend surface. As a final step, the trend is added back into the ordinary kriging result performed on the residuals. An advantage of using universal kriging for mapping rainfall IDF estimates is that it provides a direct estimate of the quality of the interpolated surface in terms of the estimation variance. Disadvantages of using universal kriging are similar to those already discussed for trend surface analysis and ordinary kriging.

Both ordinary and universal kriging deal with only one regionalized variable. In several instances, incorporating additional correlated variables may provide improvement

in interpolation. Co-kriging is a multivariate geostatistical technique that considers the spatial variation of additional variables that are correlated with the variable of interest (Burrough and McDonnell 1998). Similar to ordinary kriging, co-kriging provides an interactive process of selecting the best estimation method prior to generating the final interpolated surface. However, the interactive process in co-kriging involves computing an experimental semivariogram for each variable, overlaying the experimental semivariograms, and fitting a suitable theoretical semivariogram model to the collection. The result is the development of a theoretical covariogram. The covariogram has the same functions as the semivariogram of ordinary kriging.

Co-kriging is advantageous in situations where the variable of interest 1) is a linear combination of regionalized variables; 2) is poorly sampled but correlates highly with one or more variables that are much better sampled; or 3) exhibits low spatial autocorrelation, but correlates highly with one or more variables that exhibit relatively high continuity. While co-kriging should always provide results at least as good as those from ordinary kriging, in some situations, co-kriging may not provide significant improvement considering the additional effort required by the analyst. Therefore, Hohn (1988) suggested first obtaining kriged and cokriged results from a typical sample configuration to ensure significant improvement in the estimates is possible.

6.4 Algorithm Selection

The accuracy of an interpolated surface depends on several factors: 1) the number of observation points and the quality of the data at each point, 2) the orientation and spacing of the observations, 3) the distance between observations to be interpolated, and 4) the spatial continuity of the variable under consideration (Armstrong 1998).

Developing accurate isopluvial maps can be a challenge because there are usually a limited number of station gages that have record lengths sufficient for deriving accurate point IDF estimates. Nonetheless, an ideal method for spatial interpolation of these point estimates would do the following: 1) fit a continuous, gradually varying surface to the point estimates, 2) recognize the estimation error in the point values, 3) provide a direct means of assessing the quality of the interpolated surface, and 4) minimize subjectivity of expert judgement.

Table 6.1 compares six spatial interpolation algorithms available in a commercial geostatistical software package, based on the four criteria defining an ideal interpolation algorithm for site-specific parameters. Although kriging, in general, is considered an exact interpolator, local variation may be smoothed in order to model only the broad spatial variation by selecting a nugget size greater than zero during the development of the semivariogram and covariogram. Varying the grid size for the final interpolated surface may also incorporate some degree of smoothing of the local spatial variation. Therefore, each of the three kriging algorithms, as well as trend surface analysis, is capable of recognizing the estimation error, *i.e.* uncertainty, in the site-specific parameter. However, only the three kriging algorithms provide a direct means of assessing the quality of the interpolated surface by generating the estimation variance at each interpolated point. In addition, each of the kriging algorithms minimizes subjectivity of expert judgement by providing objective means for selecting appropriate control parameters used during the interpolation process through the semivariogram and/or covariogram. Therefore, ordinary kriging, universal, and co-kriging appear to be the most appropriate of the methods previously discussed. All three kriging algorithms are

capable of generating a continuous, gradually varying surface, providing direct estimates of the quality of the interpolated surface, and minimizing subjectivity in expert judgement.

Table 6.1. Assessment of five common spatial interpolation algorithms for appropriateness in mapping point rainfall IDF estimates.

Algorithm	**Generates continuous, gradually varying surface?**	**Recognizes uncertainties in observations?**	**Means of assessing quality of interpolation?**	**Minimizes subjectivity?**
Trend Surface Analysis	ò	ò		
Thin-Plate Splines	ò			
Inverse Distance Weighting Average				
Universal Kriging	ò	ò	ò	ò
Ordinary Kriging	ò	ò	ò	ò
Co-Kriging	ò	ò	ò	ò

Since there is a relatively small number of sample points (*i.e.*, 60 hourly recording gages) available for this study; it seems reasonable to further investigate the appropriateness of co-kriging. To determine if co-kriging is capable of significantly improving spatial interpolation results over ordinary kriging for this study, the first step is

to identify additional regionalized variables that are well correlated with rainfall IDF estimates. Distance from the closest Great Lake, elevation, and mean annual precipitation are identified as regionalized variables that one may expect to be well correlated with point rainfall IDF estimates.

Figure 6.5 illustrates a scatter plot of 2-year, 1-hour rainfall intensities versus distance from the closest Great Lake for 60 selected hourly recording stations in Michigan. The scatter plot suggests that distance from a Great Lake may be slightly correlated with the 2-year, 1-hour rainfall intensity estimates. A standard statistical t-test (DeGroot 1986) was performed to determine the significance of the slope obtained from simple linear regression. Results from the t-test showed that, at the 0.001 significance level, the null hypothesis (*i.e.*, H_0: slope = 0) should be rejected. However, such a high significance in the slope may actually be biased since there are relatively few rainfall gages 50 miles or more from a Great Lake. In addition, the low coefficient of determination (*i.e.*, $R^2 = 0.1265$) indicates rainfall IDF estimates and distance from the closest Great Lake are not well correlated.

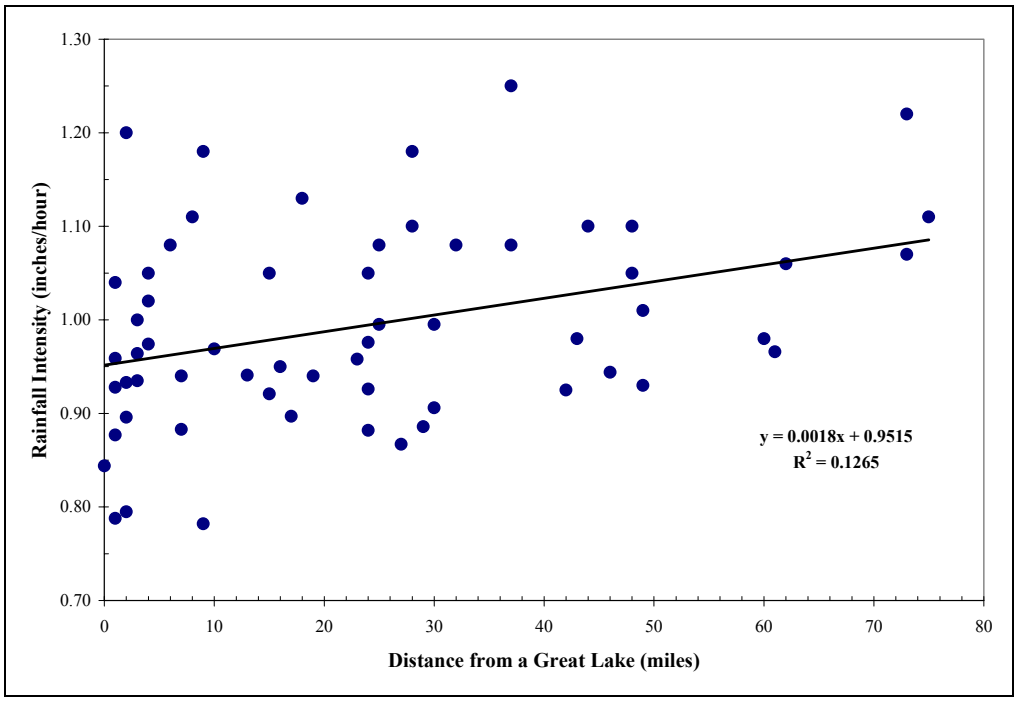

Figure 6.5. Scatter plot of 2-year, 1-hour rainfall intensities versus distance from closest Great Lake of the 60 selected hourly recording gages in Michigan.

Figure 6.6 illustrates a scatter plot of 2-year, 1-hour rainfall intensities versus recording gage elevation above mean sea level (AMSL) for the 60 hourly recording stations. The scatter plot suggests that elevation of recording gages may not be well correlated with the 2-year, 1-hour rainfall intensity estimates. A standard statistical t-test was performed to determine the significance of the slope obtained from simple linear regression. Results from the t-test showed that, at the 0.50 significance level, the null hypothesis should be rejected. Therefore, elevation of recording gages and rainfall intensity is not well correlated.

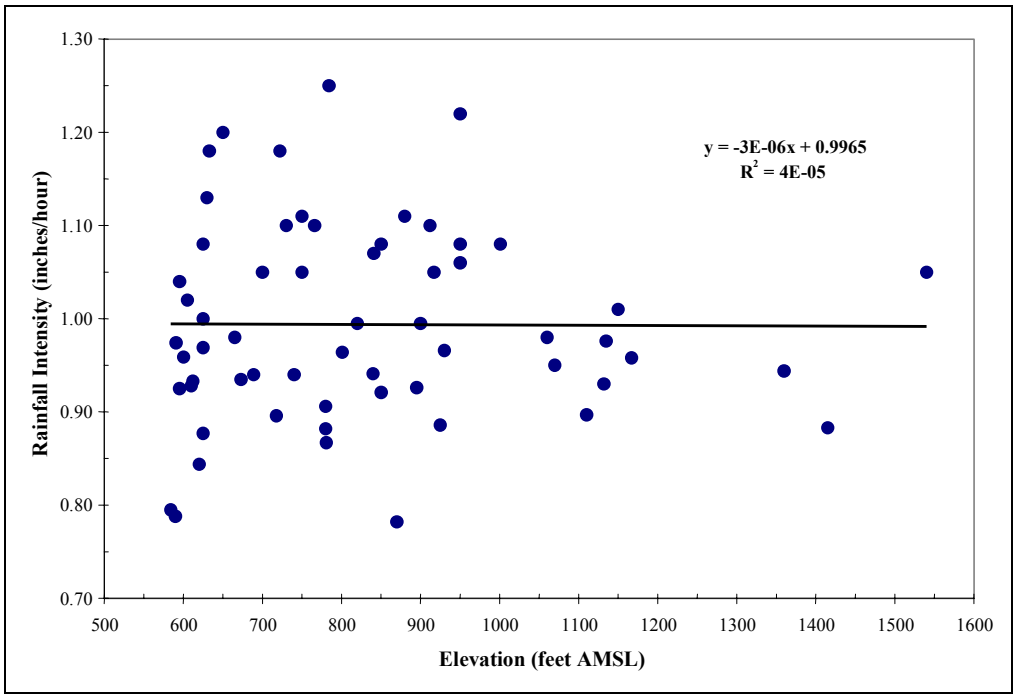

Figure 6.6. Scatter plot of 2-year, 1-hour rainfall intensities versus elevation (AMSL) of recording gages of the 60 selected hourly recording gages in Michigan.

Finally, Figure 6.7 illustrates a scatter plot of 2-year, 1-hour rainfall intensities versus mean annual precipitation for the 60 selected hourly recording stations. The scatter plot suggests that mean annual precipitation may be slightly correlated with the 2-year, 1-hour rainfall intensity estimates. A standard statistical t-test was performed to determine the significance of the slope obtained from simple linear regression. Results from the t-test showed that, at the 0.05 significance level, the null hypothesis should be rejected. However, as indicated by the low coefficient of determination (*i.e.*, R^2 = 0.0674), rainfall IDF estimates and mean annual precipitation are not well correlated. Thus, co-kriging would not be expected to offer a significant improvement over ordinary kriging or universal kriging.

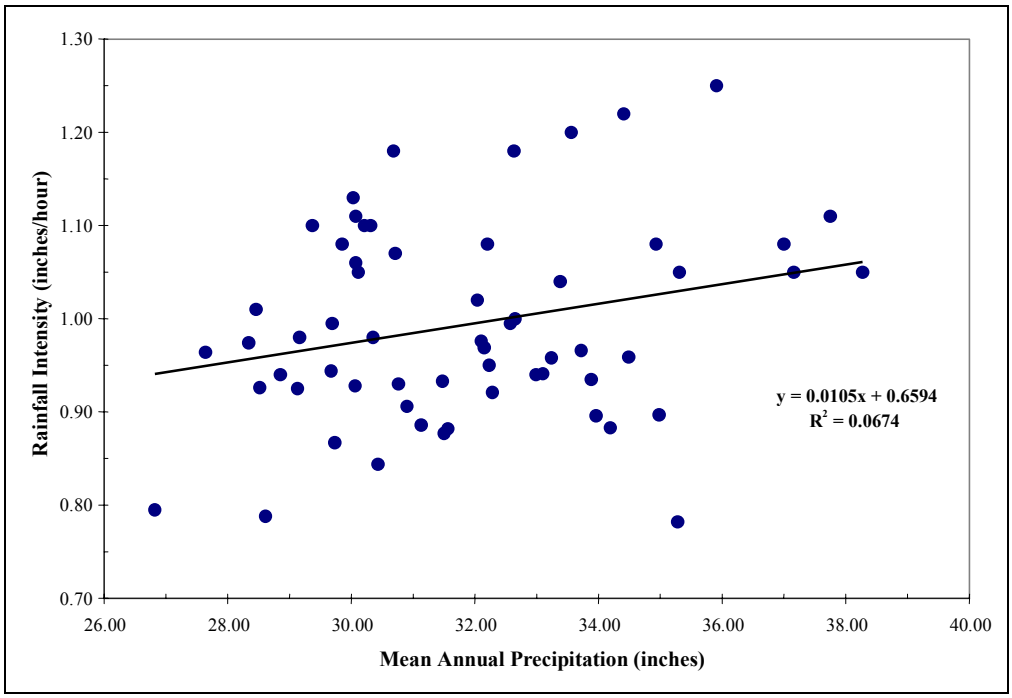

Figure 6.7. Scatter plot of 2-year, 1-hour rainfall intensities versus mean annual precipitation gages of the 60 selected hourly recording gages in Michigan.

Based on this preliminary assessment, either ordinary kriging or universal kriging appears to be the best spatial interpolation algorithm readily available for modeling the spatial behavior of the site-specific parameter in a regional analysis for this study. In Appendix D, results derived using each of these techniques are compared to results derived using trend surface analysis. The mathematical basis for kriging is also provided in greater detail in Appendix D.

6.5 Conclusion

Trend surface analysis, ordinary kriging and universal kriging appear equally capable of spatially interpolating the at-means used in this study. However, a spatial interpolation algorithm based on the moving weighted average methodology would seem

most appropriate given the nature of rainfall IDF estimates. Since universal kriging was not found to provide improved results over ordinary kriging, while introducing additional complexity, ordinary kriging appears to be the most appropriate spatial interpolation algorithm readily available for modeling the spatial variation in the at-site means for this study. Since weighting is assigned to sampled observations on a moving neighborhood basis, where the nearest observations are given greater influence at locations being estimated, the interpolated estimates are more similar to neighboring sample observations than to distant observations. Furthermore, through the selection of a semivariogram model and estimation of its parameters, the analyst can specify the size of the neighborhood.

7.0 RESULTS AND DISCUSSION

7.1 Introduction

In this chapter, five regionalization schemes are examined for selection of homogeneous region(s), and results from the AMS/GEV and PDS/GPA models are presented and discussed. In addition, comparisons are made between the recommended rainfall IDF estimates and estimates presented by Huff and Angel (1992), Sorrell and Hamilton (1990) and MDOT (1996). For brevity, results are summarized in the form of isopluvial maps, and a discussion of results for the 1- and 24-hour durations and for recurrence intervals of 2 and 100 years is provided. Results for all durations and recurrence intervals are tabulated in Appendix B, and isopluvial maps for durations of 10 minutes, 1 hour, 6 hours, and 24 hours and recurrence intervals of 2, 10, and 100 years are included in Appendix C. (A complete set of results will also be provided on a CD.) Results are also verified by comparing the observed number of exceedances of 100-year frequency rainfall intensities to the number expected.

7.2 Selection of Homogeneous Region(s)

The Michigan rainfall frequency zones currently used by MDOT, shown in Figure 7.1, were initially considered as candidate homogeneous regions for this analysis. This regionalization scheme was ruled out because Zones 3 and 4 contain only five and seven hourly recording stations, respectively, and more stations would be needed to ensure accurate quantile estimates. Through Monte Carlo simulation, Hosking and Wallis (1997) derived the regional average relative RMSE (root mean square error) of estimated

quantiles for homogeneous regions with different numbers of sites. The RMSE combines both the bias and variability of an estimate to give an overall measure of accuracy and precision (Hosking and Wallis, 1997). The relative RMSE of estimated quantiles for a homogeneous region containing only five sites was 10-12% larger than that for a homogeneous region containing 20 sites. In addition, Zone 4 exhibited high heterogeneity measures ($H > 2$) for several durations, suggesting large site-to-site variation in statistics. Thus, the current Michigan rainfall frequency zones were deemed inappropriate for a regional frequency analysis.

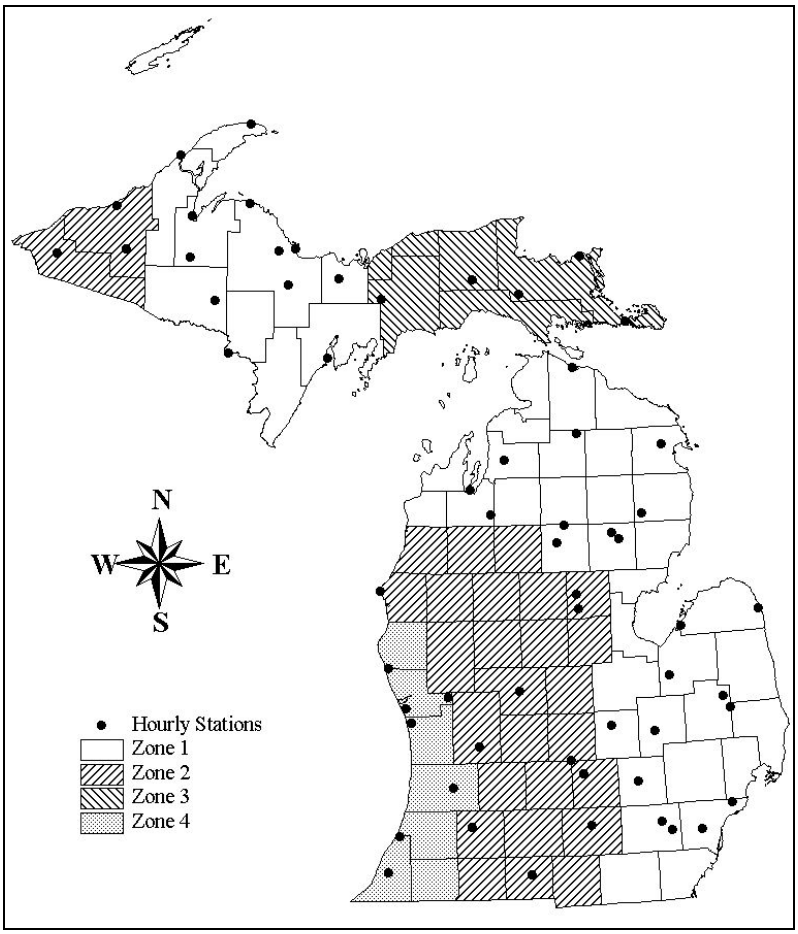

Figure 7.1. Current Michigan rainfall frequency zones, and hourly recording stations.

To identify homogeneous regions, cluster analysis based on site characteristics is recommended (Hosking and Wallis, 1997). In appraising geostatistical methods for estimating rainfall at ungaged sites, evaluated the correlation between rainfall intensity and site characteristics that are commonly associated with heavy rainfall. Little correlation was found between rainfall intensity and distance from the closest Great Lake, elevation, and mean annual precipitation. In other words, sampling variability obscures whatever correlation exists. In light of these findings, and the fact that the homogeneity criteria were satisfied with all sites lumped into one region, it was deemed that the State potentially could be treated as one homogeneous region.

To examine the possible adverse effects of treating the State as one region, three other regionalization schemes were evaluated and the resulting quantile estimates compared. Cluster analysis procedures were used to aid in identifying two or three smaller homogeneous regions within the State. Clustering was based on the following site characteristics: latitude, longitude, elevation, and mean annual precipitation (MAP). In the clustering procedure, MAP was given twice as much weight as the other site characteristics. The resulting clusters of hourly recording stations for the two and three regions are shown in Figures 7.2 and 7.3, respectively. It should be noted that the daily station clusters are identical to those in Figures 7.2 and 7.3, but with greater station density.

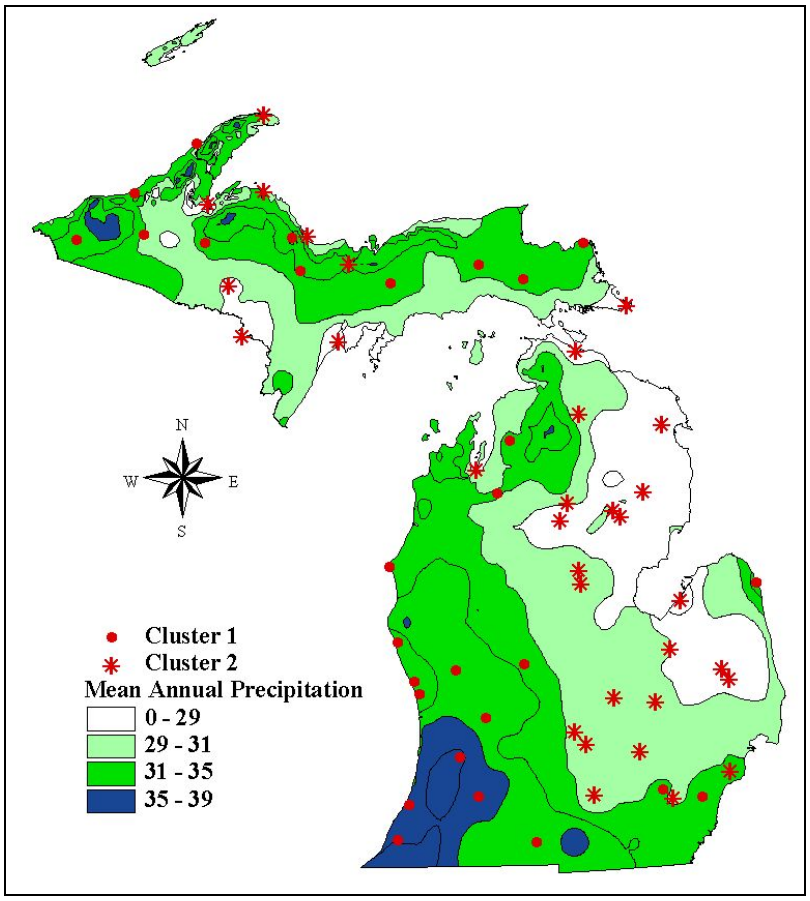

Figure 7.2. Two clusters (or regions) of hourly recording stations formed using cluster analysis procedures with mean annual precipitation given double weight.

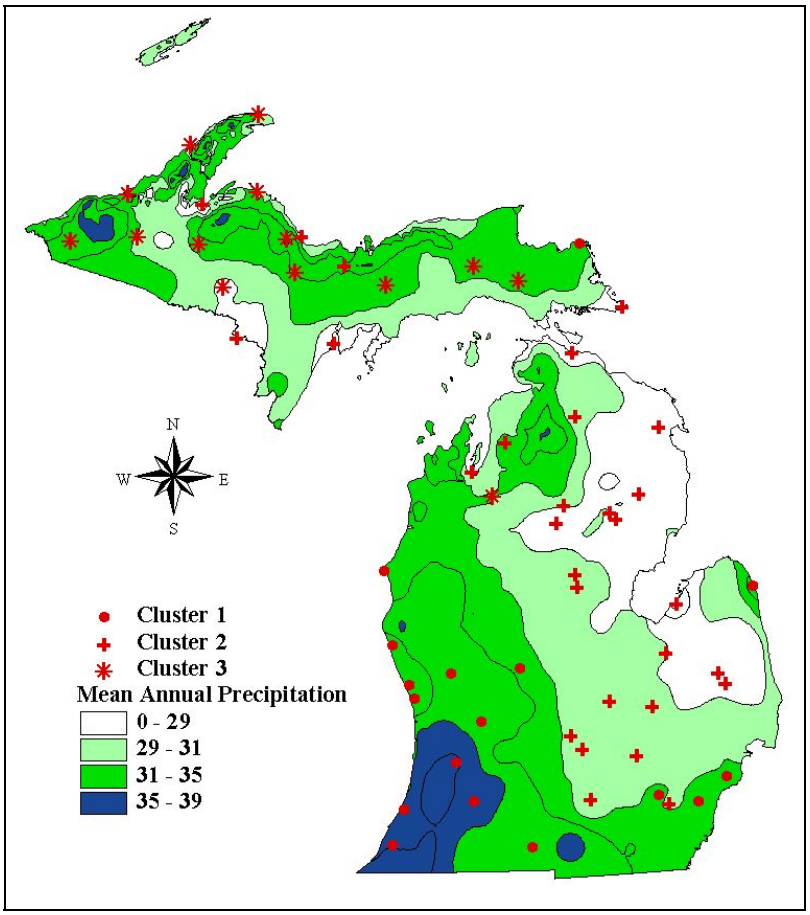

Figure 7.3. Three clusters (or regions) of hourly recording stations formed using cluster analysis procedures with mean annual precipitation given double weight.

In an effort to maximize differences in quantile estimates between two homogeneous regions within the State, a third regional scenario was evaluated. Recognizing that moist air masses from the Gulf of Mexico are a major driving force behind rainfall intensity for the Midwestern United States, the State was divided into a north region and a south region using county boundaries as a guide, as shown in Figure 7.4.

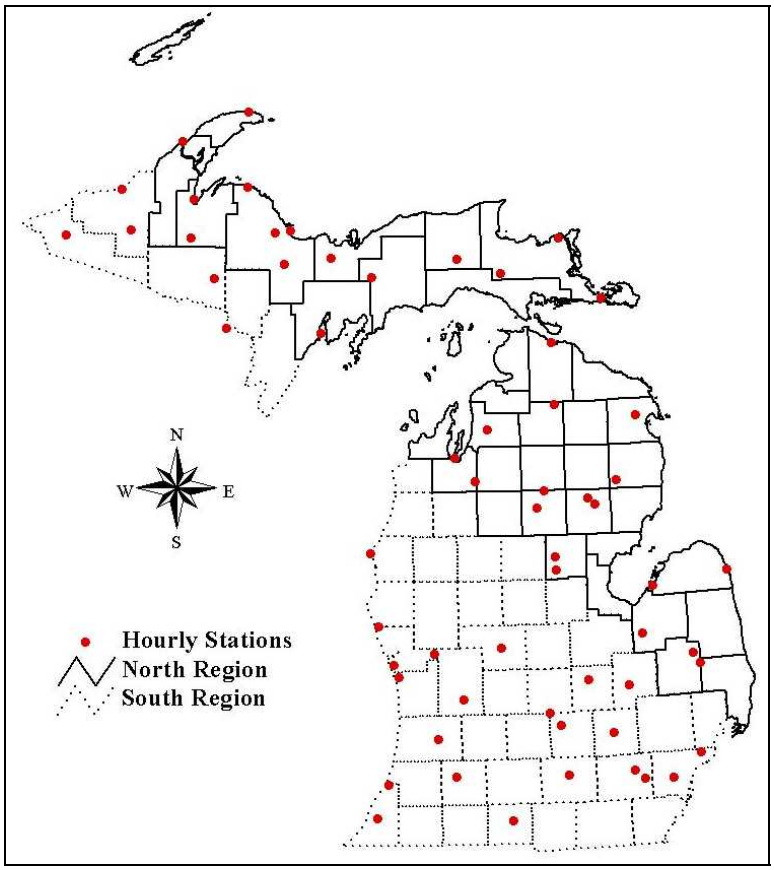

Figure 7.4. North-South regions and hourly recording gages. Regions are formed subjectively in an effort to maximize differences in regional quantile estimates.

In evaluating these regional scenarios, little variation was found between at-site statistics and the regional average statistics. As a result, heterogeneity measures were not a reliable method for determining regions (i.e., no matter how the regions were formed, the homogeneity conditions were always satisfied). Table 7.1 shows an example of this for 6-hour AMS data. For the regionalization schemes considered, the homogeneity conditions are satisfied for each cluster.

Table 7.1. Heterogeneity measures for the four regionalization schemes examined, for 6-hour AMS data (|*H*| > 2 indicates heterogeneity).

			Heterogeneity		
Cluster	Stations	Figure No.	*H*(1)	*H*(2)	*H*(3)
1	28	7.2	0.00	0.08	-0.09
2	32		-0.29	-1.39	-1.15
1	17	7.3	0.21	0.93	0.34
2	29		-0.11	-1.97	-1.85
3	14		-0.80	-0.21	0.19
North	33	7.4	-0.40	-0.90	-0.55
South	27		-0.05	-0.47	-0.71
State	60	-	-0.40	-1.08	-0.99

To further investigate the effects of considering the State as one homogeneous region, quantile estimates derived from the different regionalization schemes were compared. For this comparison, the AMS/GEV model presented in Chapter 5 was used to estimate regional quantiles for the 1-, 6-, and 24-hour durations. The regional quantile estimates were then compared by dividing those derived from the candidate regions by the quantile estimates derived from the State as one region. The results of this comparison for the two and three region scenarios are shown in Tables 7.2, 7.3, and 7.4. The quantile estimates differ by only 1-3%, with the largest differences occurring at the 100-year recurrence interval, for which the greatest variability in estimates is expected. Comparing quantile estimates between the candidate regions (or clusters), the greatest differences are observed in the three-region scenario at the 6-hour duration (see Table 7.3) and in the north-south scenario at the 1-hour duration (see Table 7.4). The differences in quantile estimates are 5% and 6%, respectively, and are again observed at the 100-year recurrence interval for which a large amount of variability is expected.

Table 7.2. Ratios of the candidate regional quantile estimates to those derived from the State as one region, for the two clusters shown in Figure 7.2.

			Regional Quantile Estimate Ratios for the *T*-year Event					
Cluster	Stations	Duration	2-year	5-year	10-year	25-year	50-year	100-year
1	28	1-hour	1.00	1.00	1.00	0.99	0.99	0.99
2	32		1.00	1.00	1.00	1.01	1.01	1.01
1	28	6-hour	1.00	1.00	1.00	1.01	1.01	1.01
2	32		1.00	1.00	1.00	0.99	0.99	0.99
1	74	24-hour	1.00	1.00	1.00	1.00	1.00	1.00
2	78		1.00	1.00	1.00	1.00	1.00	1.00

Table 7.3. Ratios of the candidate regional quantile estimates to those derived from the State as one region, for the three clusters shown in Figure 7.3.

			Regional Quantile Estimate Ratios for the *T*-year Event					
Cluster	Stations	Duration	2-year	5-year	10-year	25-year	50-year	100-year
1	17	1-hour	1.00	0.99	0.99	0.99	0.99	0.99
2	29		1.00	1.00	1.00	1.00	1.00	1.00
3	14		1.00	1.01	1.02	1.02	1.02	1.02
1	17	6-hour	0.99	1.00	1.01	1.01	1.02	1.03
2	29		1.00	1.00	0.99	0.99	0.99	0.98
3	14		1.00	1.00	1.00	1.00	1.00	1.00
1	61	24-hour	1.00	1.00	1.00	1.00	1.00	1.00
2	77		1.00	1.00	1.00	1.00	1.00	1.00
3	14		1.00	1.01	1.01	1.00	1.00	0.99

Table 7.4. Ratios of the north-south regional quantile estimates to those derived from the State as one region, for the regions shown in Figure 7.4.

			Regional Quantile Estimate Ratios for the *T*-year Event					
Cluster	Stations	Duration	2-year	5-year	10-year	25-year	50-year	100-year
North	33	1-hour	0.99	1.00	1.01	1.02	1.02	1.03
South	27		1.01	1.00	0.99	0.98	0.98	0.97
North	33	6-hour	1.00	1.00	0.99	0.99	0.99	0.99
South	27		1.00	1.00	1.01	1.01	1.01	1.01
North	74	24-hour	1.01	1.00	1.00	0.99	0.98	0.98
South	78		1.00	1.00	1.00	1.01	1.01	1.02

Because the noted differences were deemed to be insignificant for the purposes of this study, the results were derived for the State as one region.

7.3 Comparison of Annual Maximum and Partial Duration Series Results

As described in Chapter 5, the annual maximum series (AMS) and partial duration series (PDS) results were compiled using the index flood regional frequency analysis procedure outlined by Hosking and Wallis (1997), with the State considered one homogeneous region. Summaries of discordancy, heterogeneity and goodness-of-fit measures for AMS and PDS data are given in Tables 7.5 and 7.6, respectively.

The discordancy measure was used for data verification and quality control. Stations with a discordancy value of 3 or greater are considered discordant, while stations with a value of 5 or greater are highly discordant. The threshold values of 3 and 5 are not based on a rigorous test, but are considered reasonable levels to be expected within a homogeneous region (Hosking and Wallis, 1997). Considering all seven durations for the AMS data, a total of four stations were determined to be highly discordant (see Table 7.5), while in considering all eleven durations for the PDS data, six stations were found highly discordant (see Table 7.6). In most cases, these high levels of discordancy were attributed to a station observing a large outlier. It was deemed that these discordant stations contained important data for estimating extreme rainfall intensities for Michigan. Therefore, all stations were included in the analyses.

For the seven durations for the AMS data and the eleven durations for the PDS data, heterogeneity measures generally indicate that it is suitable to consider the State as one homogeneous region. Only for the 5-, 10-, 15-minute, and 1-hour PDS data was there strong evidence of heterogeneity ($|H(1)| > 2$). Because the short duration values are

the most variable of the durations considered, and the other two heterogeneity measures—$H(2)$ and $H(3)$—indicate regional homogeneity, the high values were deemed to be acceptable for the short durations.

Table 7.5. Summary of test statistics derived from annual maximum series data, considering the State as one region.

		Discordancy			Heterogeneity			Goodness-of-fit (*Z*- statistic)		
Duration	Stations	$D_i \geq 3$	$3 \leq D_i < 5$	$D_i \geq 5$	$H(1)$	$H(2)$	$H(3)$	GLO	GEV	LN3
1-hour	60	3	1	2	0.31	0.5	1.20	2.56	-2.07	-2.77
2-hour	60	5	5	0	-0.39	0.04	0.07	3.23	**-0.95**	-1.98
3-hour	60	2	1	1	-0.69	-0.43	-0.31	2.87	**-1.02**	-2.20
6-hour	60	3	2	1	-0.40	-1.08	-0.99	1.68	-1.83	-3.10
12-hour	60	4	4	0	-0.06	-1.93	-1.43	**1.14**	-2.33	-3.56
18-hour	60	2	2	0	0.29	-2.07	-1.99	**1.30**	-2.24	-3.45
24-hour	152	7	7	0	-0.64	-0.80	-0.43	1.83	-4.27	-6.80

Table 7.6. Summary of test statistics derived from partial duration series data, considering the State as one region.

		Discordancy			Heterogeneity			Goodness-of-fit (*Z*- statistic)		
Duration	Stations	$D_i \geq 3$	$3 \leq D_i < 5$	$D_i \geq 5$	$H(1)$	$H(2)$	$H(3)$	GPA	PE3	LN3
5 min	76	3	1	2	**-4.14**	-0.41	-0.19	-2.44	-1.73	4.12
10 min	76	1	1	0	**-2.17**	-0.45	-0.05	**-0.88**	**0.52**	6.56
15 min	76	2	2	0	**-2.22**	0.80	0.93	**-0.07**	**0.94**	7.16
30 min	76	4	2	2	1.15	1.33	0.92	**-0.29**	**0.34**	6.57
1-hour	60	2	1	1	**2.20**	0.18	0.48	**0.05**	-1.76	4.63
2-hour	60	3	2	1	0.12	-0.47	-0.42	**0.38**	-2.21	4.26
3-hour	60	2	2	0	-1.00	-0.53	-0.43	**0.40**	-2.60	3.87
6-hour	60	2	2	0	-1.92	-0.07	-0.33	**-0.77**	-3.73	2.44
12-hour	60	3	3	0	-2.00	-0.98	-0.90	**-0.68**	-3.81	2.37
18-hour	60	3	3	0	-1.28	-1.73	-1.74	**-0.65**	-3.54	2.67
24-hour	152	5	5	0	0.48	0.34	0.58	-1.99	-7.55	4.44

Note:
$H(1)$ - Based on L-CV only
$H(2)$ - Based on L-CV and L-skewness
$H(3)$ - Based on L-skewness and L-kurtosis
GLO - Generalized Logistic distribution
GEV - Generalized Extreme Value distribution
LN3 - Lognormal distribution
GPA - Generalized Pareto distribution
PE3 - Pearson Type III distribution

The goodness-of-fit measure Z was used to aid in identifying candidate distributions that would yield robust quantile estimates for the State. This test measures the distance between the regional average L-kurtosis and the theoretical L-kurtosis of the candidate distributions. For the five distributions tested, the three that were closest to meeting the Z criterion are shown in Tables 7.5 and 7.6. Those in bold have met the criterion of $|Z| \leq 1.64$, which corresponds to the failure to reject the hypothesized distribution at a confidence level of 90% (Hosking and Wallis, 1997).

For the AMS data (see Table 7.5), the Z-statistic is not a clear indicator of which distribution provides the best fit to the data. The GEV distribution provides the best fit for 3 durations, while the GLO distribution provides the best fit for the other 4 durations, with both satisfying the Z criterion twice. However, a literature search did not find an application of the GLO distribution to rainfall frequency analysis, while the GEV distribution and its two-parameter variant, the Gumbel distribution, have found wide application (e.g., Hershfield, 1961; Frederick, 1977; Sorrell and Hamilton, 1990; Schaefer, 1990; and Loucks et al., 2000). Furthermore, the AMS/GEV model has a close theoretical relationship with the PDS/GPA model, as discussed in Chapter 5. Thus, the GEV distribution was selected.

In contrast, the GPA distribution clearly provides the best fit to the PDS data for all 11 durations (see Table 7.6). Furthermore, the Z criterion is met for 9 of the durations. Consequently, the GPA distribution was selected to derive rainfall IDF estimates from the PDS data.

For the 24-hour duration, Tables 7.5 and 7.6 show that none of the candidate distributions meet the Z criterion. Hosking and Wallis (1997) note that this sometimes

occurs when there are numerous sites in a region, or when the at-site record lengths are large. The fact that there are 152 daily recording stations with an average record of 63 years (27 stations with over 100 years of record) incorporated in this study, which may explain why none of the candidate distributions provide an acceptable fit.

The AMS/GEV and PDS/GPA distribution parameters and regional quantile estimates (which are multiplied by the at-site means to determine IDF values) are shown in Tables 7.7 and 7.8, respectively. The AMS/GEV quantiles for the 2-, 5- and 10-year recurrence intervals have been converted to corresponding PDS values using the factors discussed in Chapter 3. Because of the arbitrary beginning and ending of an hour or day, quantile estimates from both models for the 1-, 2-, 3- and 24-hour durations have been converted from *clock-hour* quantiles to actual (*time-correct*) quantiles (see Chapter 3). Note that the PDS/GPA model regional quantile estimates are slightly larger than the AMS/GEV quantiles regardless of duration and recurrence interval. This is because the PDS/GPA quantiles are based on more frequent storm events ($F = 1-1/\lambda T$) than are the AMS/GEV quantiles ($F = 1-1/T$). Compensating for this mathematically, the PDS index floods (at-site means) are lower than the corresponding means derived from the AMS data.

For convenience, isopluvial maps were constructed to display and compare final quantile estimates. For brevity, results are for the 1- and 24-hour durations and for recurrence intervals of 2 and 100 years are discussed. Results for other selected durations and recurrence intervals are provided in Appendix C, and a complete set of results is available on the accompanying CD.

Table 7.7. AMS/GEV regional quantile estimates and GEV distribution parameters for the seven durations of interest. Quantile estimates have been adjusted by factors discussed in Chapter 3.

	Regional Quantile Estimates for the *T*-year Event						GEV Parameters		
Duration	2-year	5-year	10-year	25-year	50-year	100-year	κ	α	ξ
1-hour	1.19	1.53	1.77	2.11	2.39	2.66	-0.015	0.325	0.808
2-hour	1.08	1.40	1.63	1.96	2.24	2.52	-0.053	0.312	0.803
3-hour	1.06	1.36	1.58	1.92	2.19	2.48	-0.072	0.298	0.805
6-hour	1.04	1.32	1.53	1.86	2.13	2.42	-0.091	0.282	0.810
12-hour	1.04	1.30	1.51	1.82	2.08	2.35	-0.089	0.270	0.818
18-hour	1.05	1.30	1.50	1.81	2.06	2.33	-0.085	0.269	0.820
24-hour	1.18	1.45	1.67	2.01	2.29	2.60	-0.107	0.248	0.827

Table 7.8. PDS/GPA regional quantile estimates and GPA distribution parameters for the seven durations of interest. Quantile estimates have been adjusted by factors discussed in Chapter 3.

	Regional Quantile Estimates for the *T*-year Event						GPA Parameters		
Duration	2-year	5-year	10-year	25-year	50-year	100-year	κ	α	ξ
5 min	1.25	1.53	1.73	1.99	2.19	2.38	0.025	0.278	0.729
10 min	1.16	1.42	1.62	1.86	2.04	2.21	0.046	0.301	0.712
15 min	1.14	1.41	1.61	1.87	2.06	2.25	0.033	0.309	0.701
30 min	1.13	1.42	1.64	1.92	2.13	2.34	0.021	0.333	0.674
1-hour	1.26	1.61	1.88	2.27	2.58	2.91	-0.069	0.296	0.682
2-hour	1.15	1.47	1.74	2.12	2.43	2.77	-0.103	0.281	0.687
3-hour	1.12	1.43	1.69	2.08	2.39	2.74	-0.123	0.266	0.696
6-hour	1.09	1.39	1.64	2.00	2.31	2.64	-0.128	0.255	0.707
12-hour	1.09	1.37	1.61	1.96	2.26	2.59	-0.138	0.239	0.722
18-hour	1.09	1.37	1.60	1.94	2.23	2.53	-0.123	0.242	0.724
24-hour	1.23	1.53	1.79	2.16	2.47	2.81	-0.123	0.235	0.732

Figures 7.5 and 7.6 show 2-year AMS and PDS rainfall intensities for the 1- and 24-hour durations. In both figures, the AMS results appear to be slightly higher in magnitude than the PDS results, while the PDS values show slightly more north-south variation. The small differences in magnitude are easily attributed to the factor of 1.136 applied to convert the 2-year AMS values to PDS values.

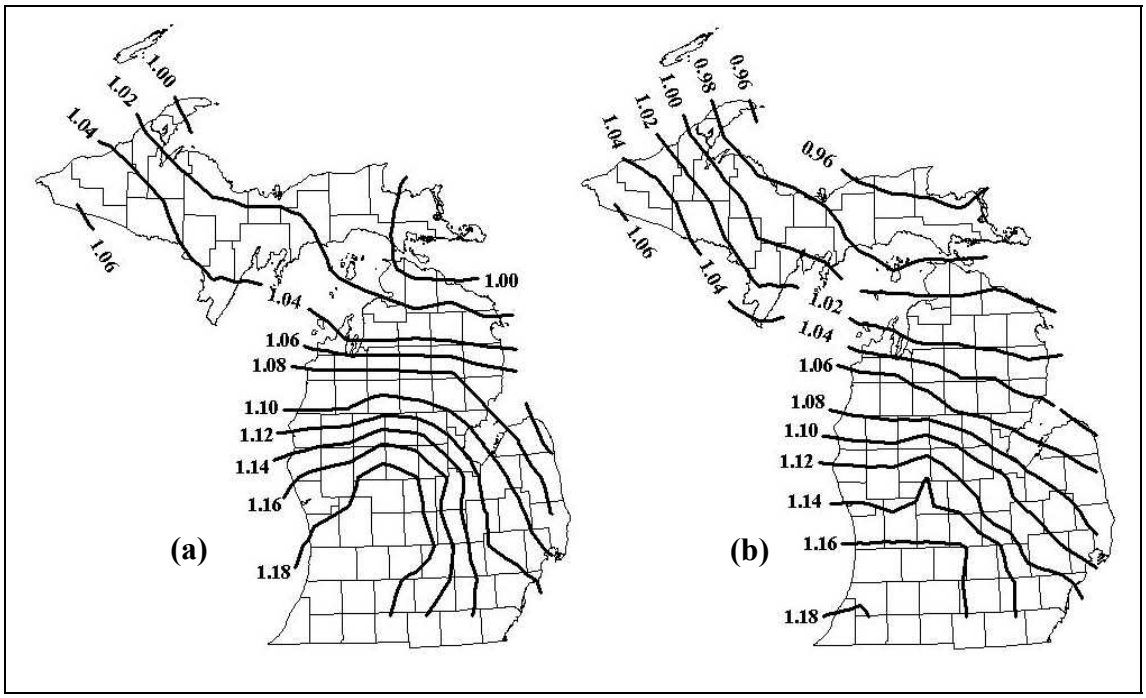

Figure 7.5. Isopluvial maps of (a) 1-hour, 2-year AMS and (b) 1-hour, 2-year PDS rainfall intensities.

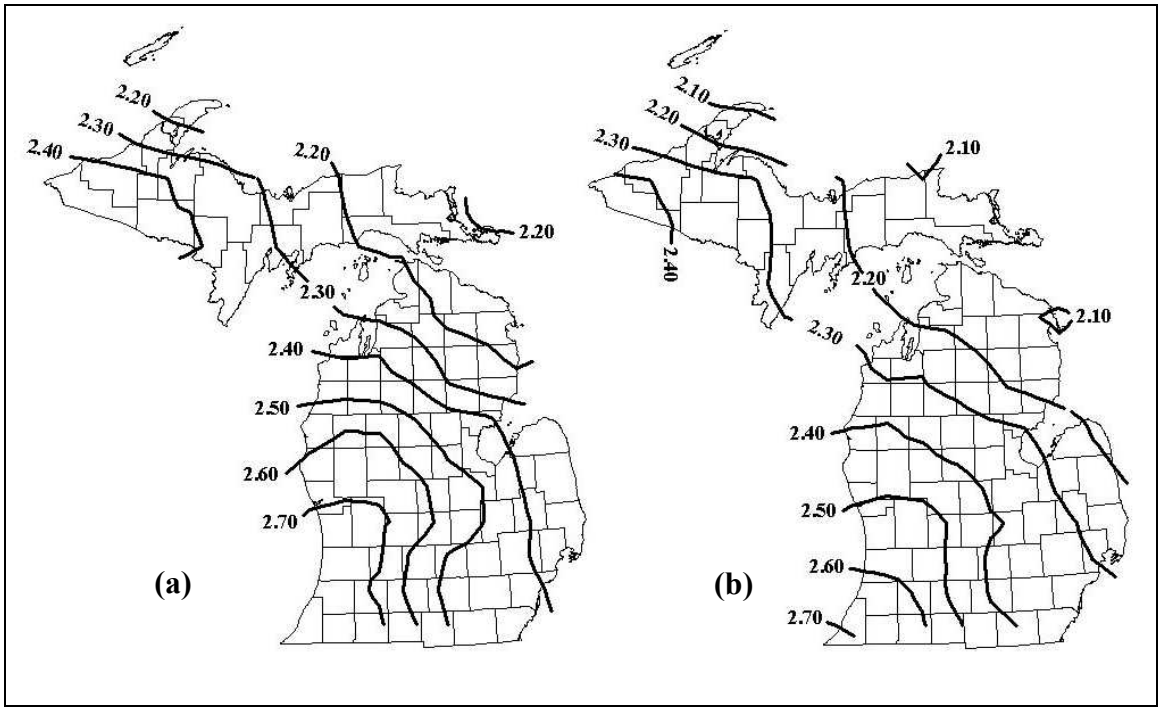

Figure 7.6. Isopluvial maps of (a) 24-hour, 2-year AMS and (b) 24-hour, 2-year PDS rainfall intensities.

The 100-year AMS and PDS rainfall intensities for 1 and 24 hours are shown in Figures 7.7 and 7.8, respectively. The 1-hour, 100-year results (Figure 7.7) are similar in magnitude, with results from both data series varying similarly across the State. Close inspection of the 24-hour, 100-year contour lines (Figure 7.8) suggests that the AMS values are slightly lower for areas in the Upper Peninsula and higher for areas in the Lower Peninsula. These differences may be expected, because the at-site means used in the AMS/GEV model were derived using data from the last half of the century (1949-96) to reflect a positive trend detected in the 24-hour (daily) data. However, for practical purposes these differences can be considered negligible.

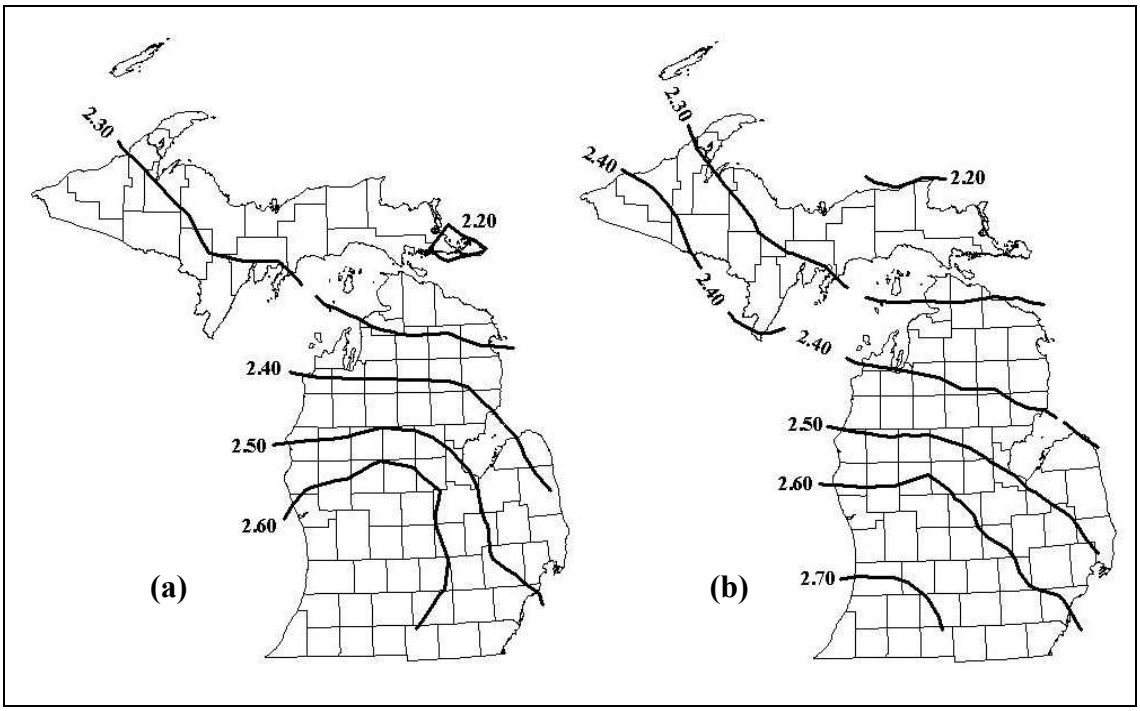

Figure 7.7. Isopluvial maps of (a) 1-hour, 100-year AMS and (b) 1-hour, 100-year PDS rainfall intensities.

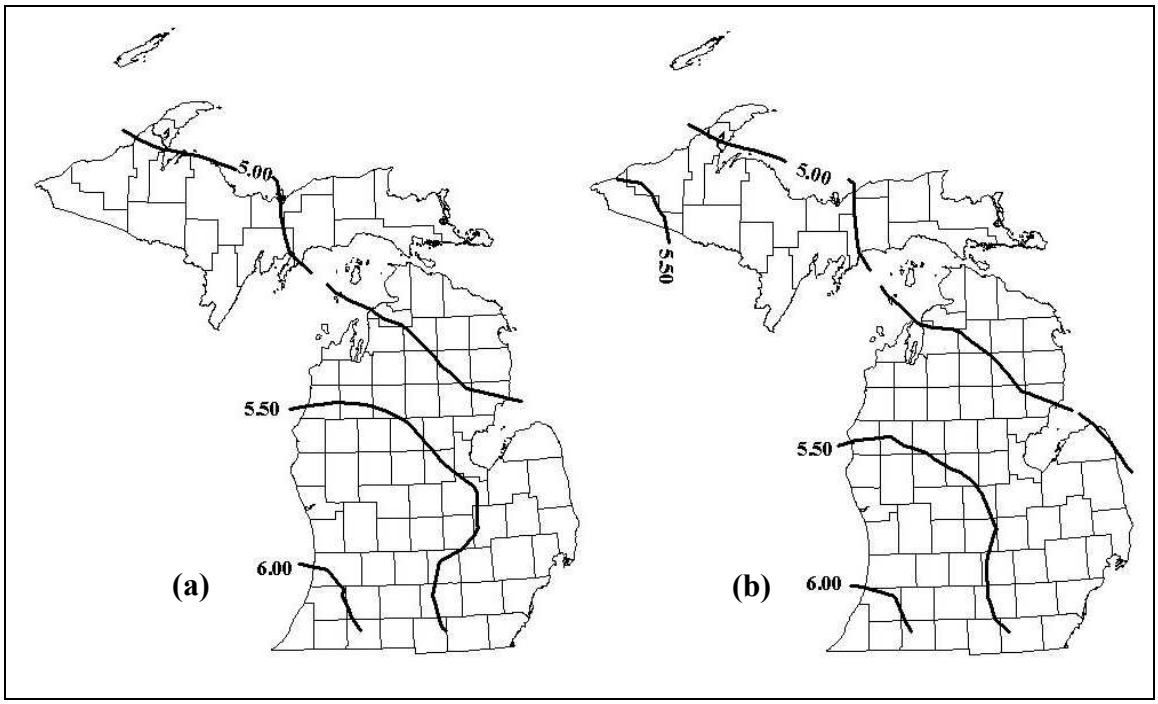

Figure 7.8. Isopluvial maps of (a) 24-hour, 100-year AMS and (b) 24-hour, 100-year PDS rainfall intensities.

7.4 Recommendations

As shown, the AMS/GEV and PDS/GPA models both provide rainfall IDF estimates that are similar in magnitude and variation across the State. Because estimates derived from AMS data rely on factors to convert them to desirable PDS results for shorter recurrence intervals, it is recommended that the direct estimates derived from the PDS data be used for the 2-, 5- and 10-year recurrence intervals. Recognizing that the differences between the two series are negligible for recurrence intervals greater than 10-years, AMS results will be used for the 25-, 50- and 100-year recurrence intervals for the durations greater than and equal to 1-hour. These AMS results also reflect the positive trend detected in the daily rainfall data for these recurrence intervals. Since AMS data was not available for the SEMCOG stations, PDS values must be used for the 25-, 50-,

and 100-year recurrence intervals for the short durations (less than 1 hour). These results, for each of the 10 climatic sections in Michigan, are summarized in tabular form in Appendix B.

7.5 Comparison with Previous Rainfall Frequency Studies

In 1992, Huff and Angel published *Bulletin 71*, *Rainfall Frequency Atlas of the Midwest* (Huff and Angel, 1992), which updated IDF estimates for nine States in the Midwest (including Michigan) for 1-hour to 10-day durations and for recurrence intervals of 2 months to 100 years. Water resources professionals in Michigan often reference the results of this study. Therefore, the results from *Bulletin 71* make for an adequate comparison to the results derived herein.

Figure 7.9 compares the 1-hour, 2-year results shown in *Bulletin 71* with those derived by the PDS/GPA model. Discrepancies of approximately 0.14 and 0.12 inches are observed, respectively, in the southwest portion of the Upper Peninsula and the southwest portion of the Lower Peninsula. Also, intensity values in *Bulletin 71* vary more across the State (0.30 inches) than do those derived from the PDS/GPA model (0.22 inches).

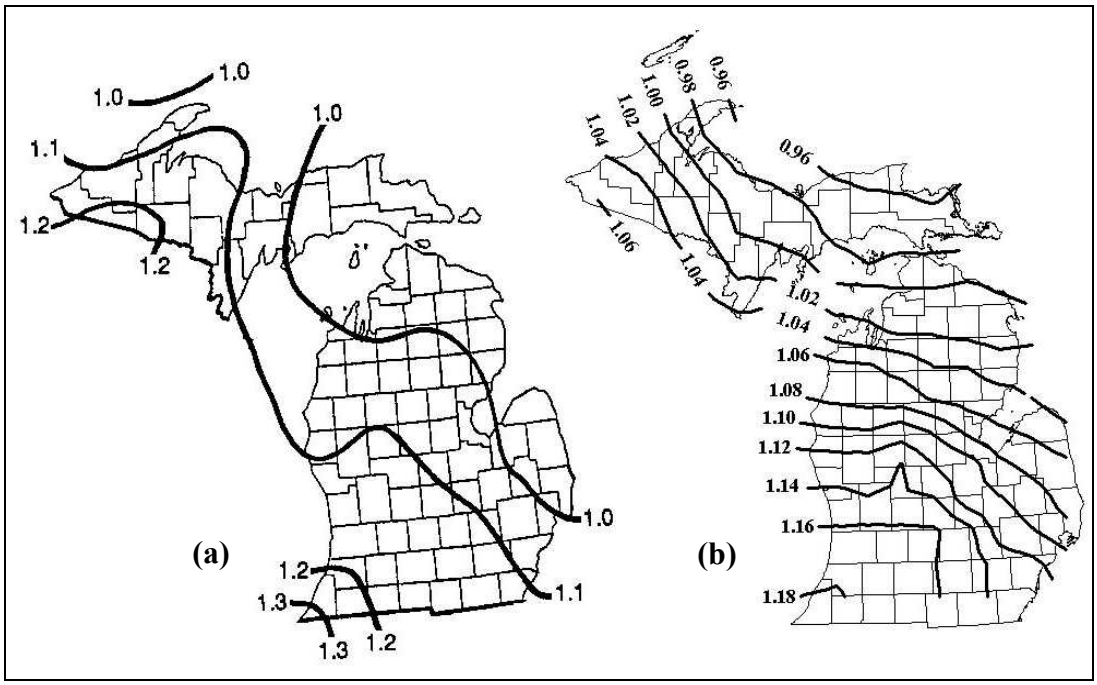

Figure 7.9. Comparison of 1-hour, 2-year rainfall intensities based on PDS results for (a) Bulletin 71, and (b) results from the PDS/GPA model.

As shown in Figure 7.10 the differences between the results for the 1-hour duration are more pronounced at the 100-year recurrence interval. The results derived from the AMS/GEV model are as much as 0.20 to 0.80 inches lower across the State in comparison to those from *Bulletin 71*. Furthermore, the results from *Bulletin 71* show a variation in estimates of 1.5 inches across the State, while the estimates derived from the AMS/GEV model vary by less than 0.50 inches.

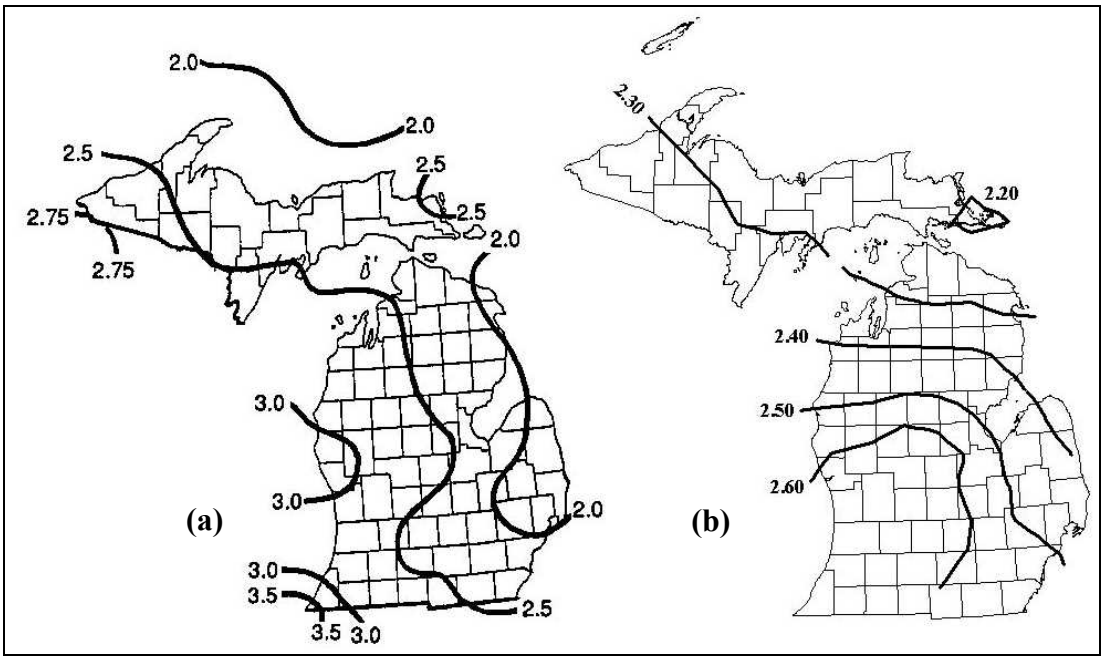

Figure 7.10. Comparison of 1-hour, 100-year rainfall intensities based on AMS results for (a) *Bulletin 71*, and (b) results from the AMS/GEV model.

The discrepancies noted at the 1-hour duration between the results of this study and those presented in *Bulletin 71* can be explained by the differences in the data used. In contrast to the hourly-recorded data from 60 stations used for durations less than 24 hours in this study, the results in *Bulletin 71* are based on rainfall data collected at 46 daily recording stations. To obtain IDF estimates for durations shorter than 24 hours, duration-specific conversion factors were applied to the 24-hour estimates. These factors were based on rainfall data collected in Illinois (34 stations) and adjacent States (21 stations). Also, to obtain 2-year PDS results, Huff and Angel (1992) converted AMS results to PDS results by a frequency-specific factor (1.13), while the results presented herein were derived from actual PDS data. Furthermore, data through 1996 were used herein, while data through only 1986 were used in *Bulletin 71*. Because of these

differences in data, it is difficult to make a direct comparison between the two studies at the 1-hour duration.

Further discrepancies noted at the 1-hour duration can be attributed to the differences in methodologies. Huff and Angel (1992) used a log-log graphical analysis to extrapolate values for the desired recurrence intervals. The log-log analysis does not assume that data fit a specific probability distribution, as was assumed in this study. Furthermore, in contrast to the regional analysis conducted herein, Huff and Angel (1992) performed an at-site analysis. This could explain why more variation is present in *Bulletin 71* results than in the results presented herein.

Results can also be compared to those given in *Rainfall Frequency for Michigan* (Sorrell and Hamilton, 1990), which updated *TP-40* 24-hour rainfall values for recurrence intervals of 2 to 100 years. Figure 7.11 compares the 24-hour, 2-year results derived by Sorrell and Hamilton (1990), Huff and Angel (*Bulletin 71*) (1992), and the PDS/GPA model. The PDS/GPA results are within ±0.15 inches of *Bulletin 71* results throughout the State, but are about 0.20 inches lower across the State than those derived by Sorrell and Hamilton (1990). All three sets of results show similar north-south variations in IDF estimates.

As shown in Figure 7.12 the 24-hour, 100-year intensities derived from the AMS/GEV model are comparable to those in *Bulletin 71*. However, notable differences are observed in the northern Upper Peninsula and the southeastern corner of the Lower Peninsula. The results derived by Sorrell and Hamilton (1990) for the 100-year recurrence interval are notably lower than those from the AMS/GEV model for northern parts of the State. IDF estimates compiled for *Bulletin 71* show a north-south variation of

3.0 inches, while those from Sorrell and Hamilton (1990) and those presented herein vary by less than 2.0 and 1.5 inches, respectively.

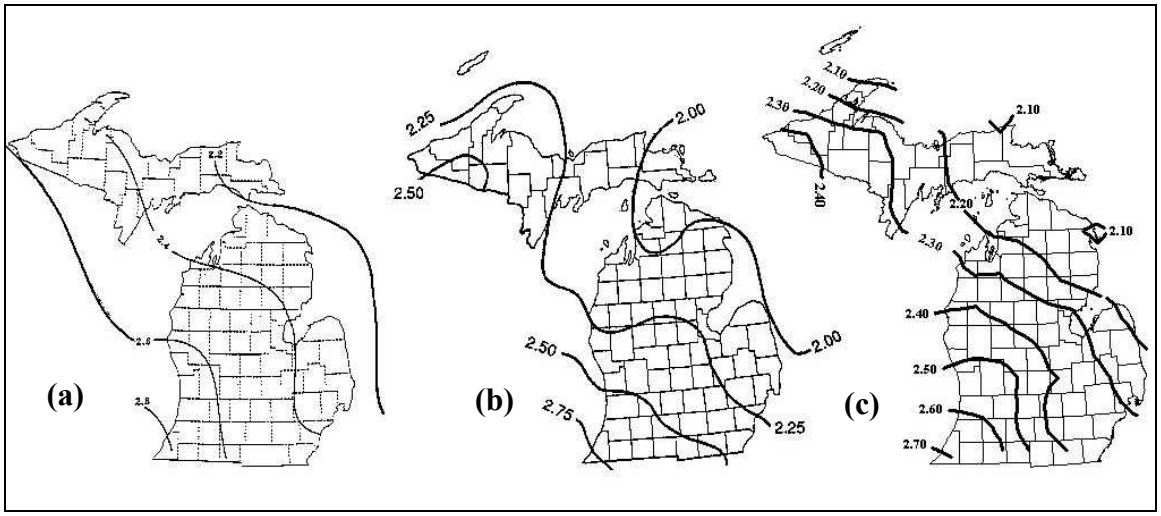

Figure 7.11. Comparison of 24-hour, 2-year rainfall intensities based on PDS results from (a) Sorrell and Hamilton (1990), (b) *Bulletin 71*, and (c) the PDS/GPA model.

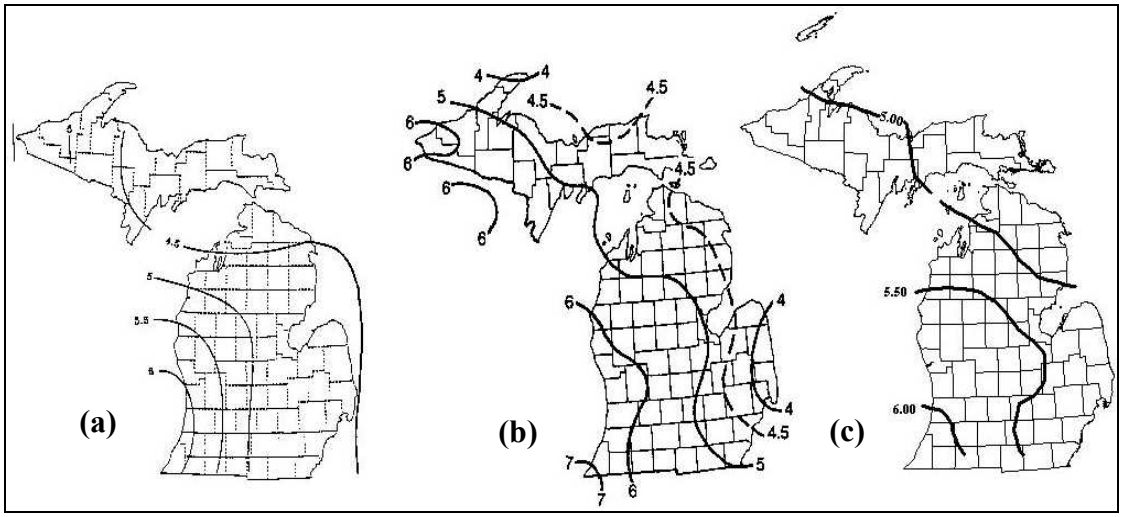

Figure 7.12. Comparison of 24-hour, 100-year rainfall intensities based on AMS results from (a) Sorrell and Hamilton (1990), (b) *Bulletin 71*, and (c) the AMS/GEV model.

Because all three studies used daily-recorded data to derive rainfall intensities for the 24-hour duration, a more direct comparison can be made. As previously discussed, discrepancies between the results of this study and *Bulletin 71* IDF estimates can be attributed to different methodologies used and the fact that 10 more years of data have been included in this analysis. It should also be noted that the results for *Bulletin 71* were derived from 46 stations with an average record length of 60 years, while this study used data from 152 stations with an average record length of 63 years. The differences between the IDF estimates presented by Sorrell and Hamilton (1990) and those of this study may be explained by the additional 9 to 16 years of data used in this study. Furthermore, in contrast to the regional approach and the three-parameter GEV and GPA distributions used herein, Sorrell and Hamilton (1990) derived at-site IDF estimates using the two-parameter Gumbel distribution and method-of-moments estimators.

7.6 Comparison with Current MDOT IDF Estimates

Currently, the MDOT *Road Design Manual* (Michigan Department of Transportation, 1996) provides rainfall intensity values for durations ranging from 10 to 240 minutes and expected recurrence intervals of 10 and 50 years. The State is divided into 4 zones for these durations and recurrence intervals, as shown in Figure 7.1, with each zone containing its own representative IDF values. The rationale for the delineation of these zones is not cited. These estimates are based on those from *TP-25* (U.S. Weather Bureau, 1955) and *TP-40* (Hershfield, 1961), but are not taken directly from those publications.

Comparisons of the current MDOT IDF estimates and the recommended IDF estimates derived herein for durations of 15 minutes, 1 hour, and 3 hours can be found in

Tables 7.9, 7.10, and 7.11. Since Zones 1 and 2 encompass areas in both the Upper Peninsula (U.P.), and Lower Peninsula (L.P.), and because MDOT applies a single value to both areas, representative values derived herein for the U.P. and L.P. are shown to demonstrate the variability between the two regions. In comparison, the current MDOT estimates are significantly larger than those developed in this study. Because it is unclear what modifications have been made to the values derived in *TP-25* and *TP-40* to arrive at the current MDOT IDF estimates, it is difficult to account for the discrepancies in these IDF values.

In the previous section, it was shown that the IDF estimates developed herein are similar to those derived by Huff and Angel (1992) and Sorrell and Hamilton (1990). Taking this into account, and the large differences noted in Tables 7.9-7.11, it appears that structures designed using the current MDOT IDF estimates for the 1-hour duration are safe and reliable structures, but are possibly over-designed.

Table 7.9. Comparison of 15-minute rainfall intensities for the 10- and 50-year recurrence intervals (U.P. – Upper Peninsula, L.P. – Lower Peninsula).

		15-min Rainfall Intensities			
		MDOT (1996)		**Updated IDF Estimates**	
Zone	Area	10-year	50-year	10-year	50-year
1	U.P.	1.10	1.49	0.78	0.99
	L.P.			0.82	1.05
2	U.P.	1.16	1.62	0.78	0.99
	L.P.			0.86	1.10
3	-	0.96	1.30	0.74	0.94
4	-	1.33	1.86	0.89	1.14

Table 7.10. Comparison of 1-hour rainfall intensities for the 10- and 50-year recurrence intervals (U.P. – Upper Peninsula, L.P. – Lower Peninsula).

		1-hour Rainfall Intensities			
		MDOT (1996)		Updated IDF Estimates	
Zone	Area	10-year	50-year	10-year	50-year
1	U.P.	2.03	2.82	1.55	2.05
	L.P.			1.65	2.20
2	U.P.	2.17	3.07	1.60	2.10
	L.P.			1.78	2.35
3	-	1.77	2.44	1.50	2.05
4	-	2.44	3.54	1.80	2.40

Table 7.11. Comparison of 3-hour rainfall intensities for the 10- and 50-year recurrence intervals (U.P. – Upper Peninsula, L.P. – Lower Peninsula).

		3-hour Rainfall Intensities			
		MDOT (1996)		Updated IDF Estimates	
Zone	Area	10-year	50-year	10-year	50-year
1	U.P.	2.48	3.43	1.98	2.56
	L.P.			2.08	2.71
2	U.P.	2.60	3.78	1.98	2.56
	L.P.			2.19	2.83
3	-	2.24	2.94	1.93	2.51
4	-	2.95	4.37	2.29	2.96

7.7 Verification of Results

To partially verify the developed IDF estimates, one can compare the *T*-year event estimate to those events actually observed. The probability, *R*, of measuring a *T*-year event or greater at a site with record length *n*, can be calculated as

$$R = 1 - \left(1 - \frac{1}{T}\right)^n . \tag{7.1}$$

For a region with N stations, the expected number of stations with observed exceedances can be approximated as

$$\text{Expected No. of Stations} \approx N * R \tag{7.2}$$

where R is computed using the average record length in the region.

This has been done for the seven longer durations (greater than and equal to an hour) by comparing the estimated AMS 100-year event to the observed maximum at each recording station. For the four short-duration stations (less than an hour), this was done by comparing the estimated PDS 100-year event to the observed maximum at each recording station. For each duration the ratio of the number of stations that have observed exceedances (X) and the number of stations expected to observe exceedances ($N*R$) has been calculated, as shown in column (7) of Table 7.10. Additionally, the probability of observing X or more stations with exceedances due to chance alone is shown in column (8) of Table 7.10. This probability was calculated using the cumulative binomial distribution function (DeGroot, 1989) as follows:

$$B(X, N, R) = \sum \binom{N}{X} R^X (1-R)^{N-X} \tag{7.3}$$

$$P(X >= x) = 1 - B(X, N, R). \tag{7.4}$$

Table 7.12. Number of stations at which the *x*-hour, 100-year value from this analysis was exceeded, with associated probabilities.

(1) Duration	(2) Number of stations (*N*)	(3) Average record length (*n*)	(4) Number of stations exceeded (X)	(5) *R*	(6) Number of stations expected (*N**R*)	(7) Ratio (X/(*N**R*))	(8) Probability (X >= x)
5-min	77	66	42	0.485	37	1.12	0.1194
10-min	77	66	36	0.485	37	0.96	0.5749
15-min	77	66	34	0.485	37	0.91	0.7406
30-min	77	66	29	0.485	37	0.78	0.9635
1-hour	60	41	29	0.338	20	1.43	0.0068
2-hour	60	41	22	0.338	20	1.09	0.2678
3-hour	60	41	23	0.338	20	1.14	0.1876
6-hour	60	41	25	0.338	20	1.23	0.0782
12-hour	60	41	22	0.338	20	1.09	0.2678
18-hour	60	41	20	0.338	20	0.99	0.4684
24-hour	152	63	66	0.469	71	0.93	0.7822

Taking into account the sampling variability associated with intense rainfall events, these ratios and probabilities of occurrences are deemed acceptable, except perhaps for the 1-hour duration. The low probability (0.0068) of 29 stations in the State observing a 100-year storm indicates that a distribution with a heavier tail than the GEV distribution may be more appropriate. However, the ratio of observed exceedances to expected exceedances (1.43) is still significantly better than the ratios computed based on the results of Sorrell and Hamilton (1990) and Hershfield (1961) (*TP-40*), which are 1.68 and 3.38, respectively (Angel and Huff, 1997).

8.0 SUMMARY AND CONCLUSION

Using data from 76 hourly and 152 daily rainfall-recording stations throughout Michigan, along with 81 Southeast Michigan Council of Governments (SEMCOG) short duration rainfall-recording stations located in 5 counties in and around the Detroit area, spatially varying rainfall intensity estimates were determined for each of eleven durations (5, 10, 15, 30, 60, 120, 180, 360, 720, 1080, and 1440 minutes) and six recurrence intervals (2, 5, 10, 25, 50 and 100 years). Both AMS and PDS data were compiled, where available, from gages with records ranging from 16 to 117 years in length. Recommended IDF estimates for 5 to 30 minutes were based on the SEMCOG data, estimates for 1 to 18 hours were derived from hourly records, and 24-hour estimates were derived from daily records.

All data were screened for gross errors by the State Climatologist, and additional checks were made using a discordancy measure. Trend analyses generally indicated increasing trends in the data (i.e., more intense storms, or more frequent storms of a given intensity, in recent years), but only in the case of the 24-hour AMS data was the trend found to be significant. A procedure for adjusting for this trend was suggested.

The frequency analysis procedure followed was the Regional L-Moment Algorithm, which is described by Hosking and Wallis (1997) and is being applied by the National Weather Service in other parts of the US. This procedure assumes that sites from a homogeneous region have an identical frequency distribution apart from a site-specific scaling factor. It was found reasonable to consider the State of Michigan as a single homogeneous region, with the mean of each site-specific data series (either AMS

or PDS) used as the scaling factor. Spatial interpolation of these site-specific factors through kriging allowed production of isopluvial maps that resemble previously used maps of rainfall intensities.

Based on goodness-of-fit statistics, the frequency distributions selected were the GEV distribution for the AMS data and the GPA distribution for the PDS data. These distributions not only provided a good fit to the data, but are expected to reliable and robust quantile estimates. Upon estimation of distribution parameters using *L*-moments, quantile (IDF) estimates were computed for regions throughout the state. The recommended IDF estimates are tabulated for the state's 10 NWS climatic sections (Appendix B), and are also illustrated in isopluvial maps (Appendix C).

The recommended IDF estimates were compared to the results of previous studies and to the design IDF values currently used by MDOT. In general, the results of this study were more similar to those presented in *Bulletin 71*, *Rainfall Frequency Atlas of the Midwest* (Huff and Angel, 1992) and *Rainfall Frequency for Michigan* (Sorrell and Hamilton, 1990) than to the IDF values given in the MDOT *Road Design Manual*, although discrepancies among all four sets of values were significant. Most notably, it was found that current MDOT estimates are significantly larger than those developed in this study. For instance, for 1-hour storms, current MDOT estimates of 10-year rainfall depths now appear to be closer to 50-year depths. Because it is unclear how the current MDOT IDF estimates were derived, based on adjustments to values derived in *TP-25* and *TP-40*, it was not possible to account for these discrepancies. However, based on verification results which indicated that the revised IDF estimates lead to approximately the number of exceedances that would be expected statistically over the period of record,

it appears that structures designed using the current MDOT IDF estimates are safe and reliable structures, but are possibly over-designed.

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Appendix A Recording Station Data

Table A.1. Properties of selected hourly recording stations (shading indicates those that have been combined with another station).

Station Name	Station ID	Years of Record	Latitude (N)	Longitude (W)
Allegan 5 NE	128	48	42.58	-85.78
Alpena WSO Airport	164	36	45.07	-83.57
Ann Arbor U of M	230	49	42.30	-83.72
Baraga 1 N	489	38	46.78	-88.48
Beaverton Power Plant	631	28	43.88	-84.48
Bellaire	662	49	44.98	-85.20
Berrien Springs 5 W	735	49	41.97	-86.43
Big Bay 8 NW	766	36	46.88	-87.87
Brown City 5 SSW	1054	26	43.12	-82.98
Bruce Crossing	1088	49	46.53	-89.18
Burnside 1 E	1133	24	43.20	-83.05
Casnovia 2 NW	1352	37	43.25	-85.82
Chatham Experiment Farm	1486	23	46.33	-86.92
Cheboygan	1492	47	45.65	-84.47
Coldwater WWTP	1680	49	41.93	-85.02
Coloma 3 NNW	1704	49	42.23	-86.32
Copper Harbor Fort Wilkins	1780	49	47.47	-87.87
Crystal Falls 6 NE	1922	42	46.17	-88.23
De Tour Village	2094	49	45.98	-83.90
Detroit City Airport	2102	49	42.42	-83.02
Detroit Metro WSCMO	2103	38	42.23	-83.32
East Lansing 4 S	2395	40	42.67	-84.48
Escanaba	2626	47	45.75	-87.03
Fife Lake 1 NNW	2788	42	44.58	-85.35
Flint WSCMO	2846	39	42.97	-83.75
Gladwin	3170	21	43.98	-84.50
Glennie Alcona Dam	3199	48	44.57	-83.80
Grand Haven WWTP	3295	49	43.07	-86.20
Grand Rapids WSFO	3333	33	42.88	-85.52
Gwinn 1 W	3516	47	46.28	-87.45
Hancock McLain State Park	3551	45	47.23	-88.62
Harbor Beach	3580	49	43.83	-82.65
Houghton Lake WSO AP	3936	33	44.37	-84.68
Howell WWTP	3947	47	42.60	-83.93
Iron Mtn-Kingsford W	4090	49	45.78	-88.08
Jackson 3 N	4155	49	42.28	-84.42
Kalamazoo State Hospital	4244	43	42.29	-85.60
Kenton	4328	47	46.48	-88.50
Lansing WSO Airport	4641	45	42.77	-84.60
Ludington State Park	4959	49	44.03	-86.50
Lupton 4 S	4966	19	44.38	-84.05
Marquette	5178	31	46.55	-87.38
Marquette WSO	5184	18	46.53	-87.55
Montague 4 NW	5567	49	43.47	-86.42
Muskegon WSO Airport	5712	49	43.17	-86.25
Newberry 3 S	5816	46	46.32	-85.50
Ontonagon	6215	48	46.85	-89.30
Owosso WWTP	6300	41	43.02	-84.18
Roscommon	7122	41	44.50	-84.60
Rose City	7134	19	44.43	-84.12
Sault Ste Marie WSO	7366	49	46.47	-84.35
Sebewaing	7419	37	43.73	-83.45
Stanton	7828	39	43.28	-85.10
Steuben	7880	42	46.18	-86.47
Traverse City	8246	39	44.77	-85.57
Trout Lake	8293	46	46.20	-85.02
Vanderbilt 11 ENE	8417	49	45.17	-84.45
Vassar	8443	38	43.37	-83.58

Table A.2. Properties of selected daily recording stations.

Station Name	Station ID	Years of Record	Latitude (N)	Longitude (W)
ADRIAN 2 NNE	32	110	41.92	-84.02
ALBERTA FFC	89	41	46.65	-88.48
ALBION	94	49	42.25	-84.77
ALLEGAN 5 NE	128	109	42.58	-85.78
ALMA	146	110	43.38	-84.67
ALPENA WSO AIRPORT	164	81	45.07	-83.58
ALPENA WWTP	169	49	45.07	-83.43
ANN ARBOR U OF M	230	117	42.30	-83.72
ATLANTA 5 WNW	343	70	45.03	-84.23
BAD AXE	417	72	43.82	-83.00
BALDWIN	446	61	43.90	-85.85
BARAGA 1 N	489	24	46.78	-88.48
BATTLE CREEK 5 NW	552	102	42.37	-85.27
BEECHWOOD 7 WNW	647	42	46.18	-88.88
BENTON HARBOR ARPT	710	110	42.13	-86.43
BERGLAND DAM	718	59	46.58	-89.55
BIG BAY 2 SE	770	28	46.80	-87.70
BIG RAPIDS WATERWORKS	779	101	43.70	-85.48
BLOOMINGDALE	864	92	42.38	-85.97
BOYNE FALLS	925	48	45.17	-84.92
CADILLAC	1176	88	44.27	-85.40
CARO REGIONAL CENTER	1299	69	43.45	-83.40
CHAMPION VAN RIPER SP	1439	48	46.52	-87.98
CHARLEVOIX	1468	49	45.32	-85.27
CHARLOTTE	1476	95	42.55	-84.83
CHATHAM EXP. FARM	1484	92	46.35	-86.93
CHEBOYGAN	1492	106	45.65	-84.47
COLDWATER STATE SCHL	1675	100	41.95	-85.00
CORNELL 4 WSW	1800	30	45.88	-87.30
CROSS VILLAGE	1896	44	45.63	-85.03
CRYSTAL FALLS 6 NE	1922	42	46.17	-88.23
DEARBORN	2015	45	42.32	-83.23
DETOUR VILLAGE	2094	49	45.99	-83.90
DETROIT CITY AIRPORT	2102	33	42.42	-83.02
DETROIT METRO WSCMO	2103	99	42.22	-83.35
DOWAGIAC 1 W	2250	49	41.98	-86.13
DUNBAR FOREST EXP ST	2298	44	46.32	-84.23
EAGLE HARBOR	2332	25	47.47	-88.17
EAST JORDAN	2381	68	45.15	-85.13
EAST LANSING EXPERIM	2393	51	42.70	-84.47
EAST LANSING WB CITY	2394	48	42.73	-84.48
EAST LANSING 4 S	2395	87	42.67	-84.48
EAST TAWAS	2423	65	44.28	-83.50
EATON RAPIDS	2437	49	42.52	-84.65
EAU CLAIRE 4 NE	2445	73	42.02	-86.25
ESCANABA	2626	47	45.75	-87.03
ESSEXVILLE	2631	101	43.62	-83.87
EVART	2671	47	43.92	-85.27
FAYETTE 4 SW	2737	66	45.67	-86.72
FIFE LAKE 4 SW	2784	36	44.55	-85.42

TableA.2. (Cont'd) Properties of selected daily recording stations.

Station Name	Station ID	Years of Record	Latitude (N)	Longitude (W)
FLINT WSCMO	2846	104	42.97	-83.75
FRANKFORT 2 NE	2984	33	44.65	-86.20
GAYLORD	3096	92	45.03	-84.67
GLADWIN	3170	71	43.98	-84.48
GRAND HAVEN FIRE DEP	3290	64	43.07	-86.22
GRAND LEDGE 1 NW	3306	49	42.77	-84.77
GRAND MARAIS 2 E	3319	97	46.67	-85.95
GRAND RAPIDS WSFO	3333	49	42.88	-85.52
GRAYLING	3391	106	44.65	-84.70
GREENVILLE 2 NNE	3429	85	43.20	-85.25
GROSSE POINTE FARMS	3477	46	42.38	-82.90
GULL LAKE BIOL STA	3504	49	42.40	-85.38
HALE LOUD DAM	3529	49	44.47	-83.72
HARBOR BEACH 1 SSE	3585	65	43.83	-82.63
HARRISON 1 NNW	3616	38	44.03	-84.80
HART	3632	74	43.68	-86.35
HASTINGS	3661	82	42.65	-85.28
HERMAN	3744	29	46.67	-88.35
HESPERIA 4 WNW	3769	56	43.58	-86.10
HIGGINS LAKE	3785	71	44.52	-84.75
HILLSDALE	3823	43	41.93	-84.63
HOLLAND	3858	92	42.78	-86.12
HOUGHTON FAA AIRPORT	3908	110	47.17	-88.50
HOUGHTON LAKE 6 WSW	3932	51	44.32	-84.90
HOUGHTON LAKE WSO AP	3936	33	44.37	-84.68
HOWELL WWTP	3947	49	42.60	-83.93
IONIA 2 SSW	4078	48	42.95	-85.08
IRON MTN-KINGSFORD W	4090	66	45.78	-88.08
IRONWOOD	4104	96	46.47	-90.18
ISHPEMING	4127	90	46.48	-87.65
JACKSON FAA ARPT	4150	100	42.27	-84.47
KALAMAZOO STATE HOSP	4244	104	42.28	-85.60
KALKASKA	4257	49	44.73	-85.17
KENT CITY 2 SW	4320	78	43.20	-85.77
KENTON	4328	57	46.48	-88.88
LAKE CITY EXP FARM	4502	66	44.32	-85.20
LANSING WSO AIRPORT	4641	49	42.78	-84.58
LAPEER WWTP	4655	96	43.07	-83.30
LOWELL	4944	49	42.93	-85.33
LUDINGTON 4 SE	4954	101	43.90	-86.40
LUPTON 1 S	4967	46	44.42	-84.02
MACKINAW CITY LIGHT	5000	25	45.78	-84.73
MANISTEE 3 SE	5065	101	44.22	-86.30
MANISTIQUE	5073	49	45.95	-86.25
MAPLE CITY	5097	38	44.85	-85.85
MARQUETTE	5178	49	46.55	-87.38
MARQUETTE WSO	5184	36	46.53	-87.55
MIDLAND	5434	89	43.62	-84.22
MILFORD GM PROV. GRNDS	5452	66	42.58	-83.70
MILLINGTON 3 SW	5488	49	43.23	-83.57
MIO HYDRO PLANT	5531	49	44.67	-84.13

Table A.2. (Cont'd) Properties of selected daily recording stations.

Station Name	Station ID	Years of Record	Latitude (N)	Longitude (W)
MONROE	5558	80	41.92	-83.40
MONTAGUE 4 NW	5567	47	43.47	-86.42
MOTT ISLAND ISLE ROY	5637	45	48.10	-88.55
MOUNT CLEMENS ANG BA	5650	63	42.62	-82.83
MT PLEASANT UNIV	5662	98	43.58	-84.77
MUNISING	5690	53	46.42	-86.67
MUSKEGON WSO AIRPORT	5712	101	43.17	-86.23
NEWBERRY 3 S	5816	101	46.32	-85.50
NILES	5892	49	41.83	-86.27
ONAWAY STATE PARK	6184	49	45.43	-84.23
OWOSSO WWTP	6300	97	43.02	-84.18
PELLSTON AIRPORT	6438	49	45.57	-84.78
PETOSKEY	6507	45	45.37	-84.98
PONTIAC STATE HOSPIT	6658	89	42.65	-83.30
PORT HURON	6680	66	42.98	-82.42
PORT INLAND	6686	37	45.97	-85.87
ROCK 1 E	7068	43	46.07	-87.15
ROGERS CITY 3 S	7089	26	45.38	-83.83
RUDYARD 4 N	7190	49	46.30	-84.58
SAGINAW CONSUMERS PW	7217	33	43.45	-83.97
SAGINAW FAA AIRPORT	7227	101	43.53	-84.08
SAINT CHARLES	7253	33	43.30	-84.17
ST IGNACE MACKINAC B	7274	24	45.85	-84.72
ST JAMES 2 S BEAVER	7277	40	45.72	-85.52
ST JOHNS	7280	59	43.02	-84.55
SANDUSKY	7350	46	43.42	-82.82
SAULT STE MARIE WSO	7366	58	46.47	-84.35
SCOTTVILLE 1 NE	7405	31	43.97	-86.27
SEBEWAING	7419	43	43.73	-83.45
SENEY WILDLIFE REFUG	7515	49	46.28	-85.95
SOUTH HAVEN	7690	71	42.40	-86.28
SPALDING 1 SSE	7742	44	45.68	-87.50
STAMBAUGH 2 SSE	7812	98	46.05	-88.62
STANDISH 5 SW	7820	59	43.95	-84.03
STEPHENSON 8 WNW	7867	49	45.45	-87.75
STEUBEN	7880	42	46.18	-86.47
SUTTONS BAY 4 NW	8032	21	45.02	-85.70
TAHQUAMENON FALLS ST	8043	24	46.60	-85.22
THOMPSONVILLE	8167	36	44.52	-85.93
THREE RIVERS	8184	54	41.93	-85.63
TRAVERSE CITY FAA AP	8251	101	44.73	-85.58
VANDERBILT 11 ENE	8417	66	45.17	-84.43
WASHINGTON	8650	39	42.73	-83.03
WATERSMEET	8680	59	46.28	-89.17
WELLSTON TIPPY DAM	8772	49	44.25	-85.93
WEST BRANCH 3 SE	8800	97	44.25	-84.20
WHITEFISH POINT	8920	79	46.75	-84.98
WILLIAMSTON 3 NE	9006	44	42.72	-84.25
WILLIS 5 SSW	9014	36	42.08	-83.58
YALE 1 NNW	9188	43	43.15	-82.80
YPSILANTI E MICH UNI	9218	45	42.23	-83.62

Table A.3. Properties of SEMCOG short duration recording stations

Station Name	Station ID	Years of Record	Latitude (N)	Longitude (W)
ANN ARBOR	A-01	30	42.29	-83.84
PINCKNEY	A-02	29	42.45	-84.02
CHELSEA	A-03	28	42.27	-84.04
YPSILANTI	A-04	29	42.23	-83.61
YPSILANTI	A-05	28	42.25	-83.63
FOWLERVILLE	L-01	29	42.67	-84.08
FOWLERVILLE	L-02	21	42.74	-84.10
COHOCTAH 4S	L-03	21	42.71	-83.95
HOWELL	L-04	18	42.59	-83.93
GREGORY	L-05	21	42.50	-84.11
HAMBURG	L-06	21	42.44	-83.80
BRIGHTON	L-07	21	42.53	-83.79
HARTLAND	L-08	21	42.74	-83.75
ARMADA	M-01	35	42.84	-82.88
MT. CLEMENS	M-02	35	42.60	-82.87
ST. CLAIR SHORES	M-03	31	42.47	-82.91
MT. CLEMENS	M-04	36	42.58	-82.80
MT. CLEMENS	M-05	32	42.56	-82.87
UTICA	M-06	35	42.66	-83.01
STONY CREEK PARK	M-07	37	42.76	-83.07
ROMEO	M-08	37	42.80	-82.98
STERLING HEIGHTS	M-09	34	42.59	-83.04
MT. CLEMENS	M-10	19	42.58	-82.95
FARMINGTON	O-01	25	42.53	-83.36
BERKLEY	O-02	37	42.51	-83.19
TROY	O-03	36	42.59	-83.13
LAKEVILLE	O-04	37	42.81	-83.13
CLARKSTON	O-05	37	42.74	-83.39
BIRMINGHAM	O-06	33	42.54	-83.21
PONTIAC	O-07	37	42.66	-83.34
PONTIAC	O-08	37	42.64	-83.25
LAKE ORION	O-09	36	42.74	-83.24
MILFORD	O-10	37	42.58	-83.63
WHITE LAKE	O-11	35	42.65	-83.51
WIXOM 1W	O-12	18	42.55	-83.54
NOVI	O-13	37	42.51	-83.50
OXFORD	O-14	30	42.85	-83.20
HOLLY	O-16	28	42.80	-83.63
HAZEL PARK	O-17	35	42.46	-83.10
OAK PARK	O-18	37	42.47	-83.18
SOUTHFIELD	O-19	37	42.50	-83.29
CRANBERRY LAKE	O-21	33	42.66	-83.47
MADISON HEIGHTS	O-22	34	42.50	-83.12
TROY-ROCKWELL	O-25	29	42.55	-83.17
WIXOM	O-26	29	42.50	-83.54
ROCHESTER	O-27	21	42.68	-83.13
DEARBORN	W-08	37	42.30	-83.18
DETROIT	W-09	28	42.42	-83.27
DETROIT	W-12	28	42.44	-83.10
DETROIT	W-13	25	42.41	-83.01
DETROIT	W-14	37	42.40	-82.92
DETROIT	W-15	36	42.37	-82.96
DETROIT	W-16	37	42.35	-83.15
DETROIT	W-17	16	42.39	-83.13
DETROIT	W-18	37	42.44	-83.01
DETROIT	W-19	37	42.33	-83.04
DETROIT	W-20	38	42.31	-83.14
DETROIT	W-22	37	42.27	-83.23
DEARBORN	W-23	37	42.30	-83.27
DETROIT	W-25	37	42.44	-83.18
LIVONIA	W-26	36	42.37	-83.35
DETROIT	W-27	37	42.36	-83.25
DETROIT	W-28	29	42.41	-82.96
DETROIT	W-29	37	42.34	-83.05
DETROIT	W-30	26	42.40	-82.99
GROSSE POINT SHORES	W-31	31	42.44	-82.88
MILK RIVER	W-33	31	42.45	-82.89
TRENTON	W-35	30	42.13	-83.19
DEARBORN	W-36	21	42.31	-83.22
PLYMOUTH	W-38	20	42.37	-83.48
LIVONIA	W-39	23	42.37	-83.33
GROSSE POINT WOODS	W-42	26	42.43	-82.90

Appendix B Recommended IDF Estimates

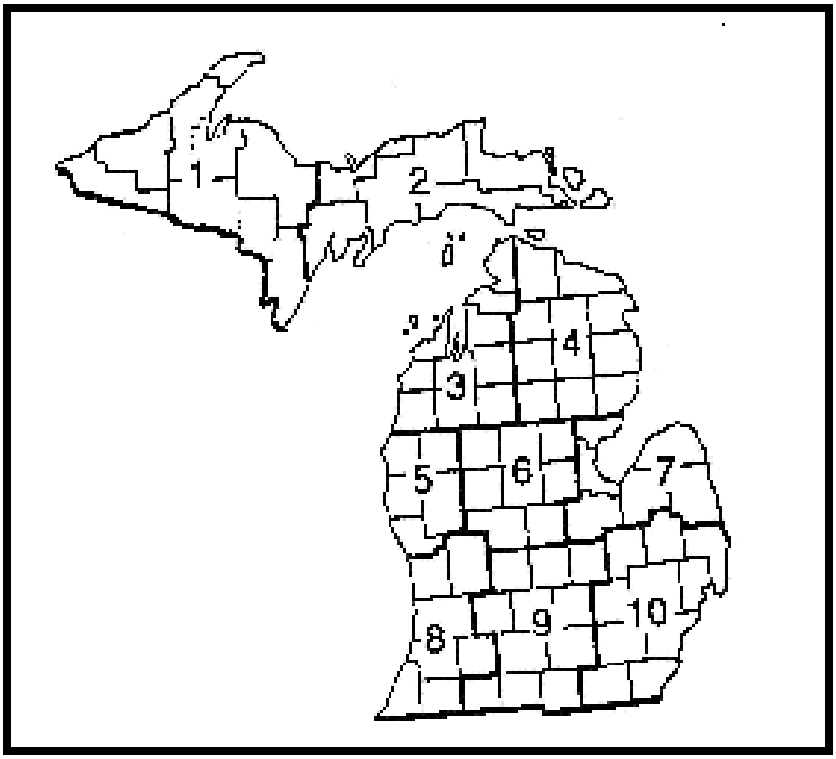

Figure B.1. NWS Climatic Zones

Table B.1. Recommended IDF Estimates for 10 Climatic Zones (values in inches)

Zone 1						
Duration (min)	**2-yr**	**5-yr**	**10-yr**	**25-yr**	**50-yr**	**100-yr**
5	0.30	0.37	0.42	0.48	0.53	0.57
10	0.46	0.57	0.64	0.74	0.81	0.88
15	0.55	0.68	0.78	0.90	0.99	1.08
30	0.74	0.94	1.08	1.26	1.40	1.54
60 (1-hr)	1.02	1.30	1.53	1.83	2.07	2.31
120 (2-hr)	1.19	1.52	1.80	2.19	2.50	2.81
180 (3-hr)	1.31	1.68	1.98	2.23	2.56	2.89
360 (6-hr)	1.54	1.95	2.30	2.79	3.20	3.64
720 (12-hr)	1.82	2.29	2.69	3.24	3.70	4.20
1080 (18-hr)	1.98	2.49	2.91	3.51	4.01	4.53
1440 (24-hr)	2.38	2.97	3.47	4.19	4.79	5.43

Zone 2						
Duration (min)	**2-yr**	**5-yr**	**10-yr**	**25-yr**	**50-yr**	**100-yr**
5	0.29	0.35	0.40	0.46	0.50	0.55
10	0.44	0.54	0.61	0.70	0.77	0.84
15	0.52	0.65	0.74	0.86	0.94	1.03
30	0.71	0.89	1.03	1.20	1.33	1.46
60 (1-hr)	0.97	1.24	1.45	1.79	2.02	2.05
120 (2-hr)	1.16	1.48	1.75	2.17	2.47	2.79
180 (3-hr)	1.28	1.64	1.93	2.19	2.51	2.84
360 (6-hr)	1.50	1.90	2.24	2.76	3.17	3.60
720 (12-hr)	1.71	2.16	2.53	3.12	3.57	4.04
1080 (18-hr)	1.87	2.34	2.74	3.33	3.80	4.30
1440 (24-hr)	2.26	2.82	3.29	3.95	4.51	5.12

Zone 3						
Duration (min)	**2-yr**	**5-yr**	**10-yr**	**25-yr**	**50-yr**	**100-yr**
5	0.31	0.38	0.43	0.49	0.54	0.59
10	0.47	0.58	0.66	0.76	0.83	0.90
15	0.56	0.70	0.80	0.92	1.02	1.11
30	0.76	0.96	1.10	1.29	1.44	1.58
60 (1-hr)	1.03	1.32	1.55	1.89	2.13	2.38
120 (2-hr)	1.24	1.58	1.87	2.30	2.63	2.96
180 (3-hr)	1.36	1.74	2.06	2.33	2.67	3.02
360 (6-hr)	1.58	2.01	2.37	2.95	3.38	3.84
720 (12-hr)	1.83	2.30	2.70	3.39	3.88	4.39
1080 (18-hr)	1.99	2.50	2.92	3.59	4.10	4.63
1440 (24-hr)	2.37	2.96	3.45	4.22	4.83	5.48

Zone 4						
Duration (min)	**2-yr**	**5-yr**	**10-yr**	**25-yr**	**50-yr**	**100-yr**
5	0.30	0.37	0.42	0.48	0.53	0.58
10	0.46	0.57	0.64	0.74	0.81	0.88
15	0.55	0.68	0.78	0.90	0.99	1.08
30	0.74	0.94	1.08	1.27	1.40	1.54
60 (1-hr)	1.02	1.30	1.52	1.85	2.09	2.33
120 (2-hr)	1.19	1.52	1.80	2.22	2.53	2.85
180 (3-hr)	1.31	1.68	1.98	2.24	2.56	2.90
360 (6-hr)	1.52	1.94	2.28	2.81	3.23	3.67
720 (12-hr)	1.75	2.20	2.59	3.11	3.56	4.03
1080 (18-hr)	1.89	2.38	2.78	3.35	3.83	4.33
1440 (24-hr)	2.26	2.82	3.29	3.95	4.52	5.13

Zone 5						
Duration (min)	**2-yr**	**5-yr**	**10-yr**	**25-yr**	**50-yr**	**100-yr**
5	0.33	0.40	0.46	0.53	0.58	0.63
10	0.51	0.62	0.71	0.81	0.89	0.97
15	0.60	0.75	0.85	0.99	1.09	1.19
30	0.81	1.03	1.18	1.39	1.54	1.69
60 (1-hr)	1.12	1.42	1.67	2.05	2.31	2.57
120 (2-hr)	1.33	1.70	2.01	2.47	2.81	3.17
180 (3-hr)	1.47	1.87	2.21	2.49	2.85	3.23
360 (6-hr)	1.73	2.20	2.59	3.16	3.63	4.12
720 (12-hr)	2.00	2.52	2.96	3.73	4.27	4.83
1080 (18-hr)	2.19	2.75	3.22	4.02	4.59	5.19
1440 (24-hr)	2.60	3.25	3.79	4.77	5.45	6.19

Zone 6						
Duration (min)	**2-yr**	**5-yr**	**10-yr**	**25-yr**	**50-yr**	**100-yr**
5	0.33	0.41	0.46	0.53	0.58	0.64
10	0.51	0.63	0.71	0.82	0.90	0.97
15	0.61	0.75	0.86	1.00	1.10	1.19
30	0.82	1.03	1.19	1.40	1.55	1.70
60 (1-hr)	1.11	1.42	1.66	2.09	2.36	2.62
120 (2-hr)	1.31	1.68	1.99	2.46	2.81	3.16
180 (3-hr)	1.45	1.85	2.19	2.47	2.83	3.20
360 (6-hr)	1.67	2.12	2.50	3.09	3.54	4.02
720 (12-hr)	1.92	2.42	2.85	3.46	3.96	4.49
1080 (18-hr)	2.10	2.63	3.08	3.78	4.31	4.88
1440 (24-hr)	2.50	3.12	3.64	4.44	5.08	5.77

Zone 7						
Duration (min)	**2-yr**	**5-yr**	**10-yr**	**25-yr**	**50-yr**	**100-yr**
5	0.32	0.39	0.44	0.51	0.56	0.61
10	0.49	0.60	0.68	0.78	0.86	0.93
15	0.58	0.72	0.82	0.96	1.05	1.15
30	0.79	0.99	1.14	1.34	1.49	1.63
60 (1-hr)	1.05	1.34	1.57	1.96	2.22	2.47
120 (2-hr)	1.26	1.61	1.90	2.36	2.70	3.04
180 (3-hr)	1.38	1.76	2.08	2.37	2.71	3.07
360 (6-hr)	1.57	1.99	2.35	2.93	3.36	3.82
720 (12-hr)	1.81	2.29	2.68	3.21	3.67	4.16
1080 (18-hr)	1.98	2.48	2.90	3.52	4.02	4.54
1440 (24-hr)	2.38	2.97	3.46	4.15	4.75	5.38

Zone 8						
Duration (min)	**2-yr**	**5-yr**	**10-yr**	**25-yr**	**50-yr**	**100-yr**
5	0.35	0.42	0.48	0.55	0.61	0.66
10	0.53	0.65	0.74	0.85	0.93	1.01
15	0.63	0.78	0.89	1.03	1.14	1.24
30	0.85	1.07	1.24	1.45	1.61	1.77
60 (1-hr)	1.16	1.48	1.74	2.10	2.37	2.64
120 (2-hr)	1.38	1.76	2.08	2.52	2.87	3.23
180 (3-hr)	1.52	1.94	2.29	2.59	2.96	3.35
360 (6-hr)	1.79	2.27	2.68	3.24	3.72	4.22
720 (12-hr)	2.07	2.61	3.06	3.74	4.27	4.84
1080 (18-hr)	2.25	2.83	3.31	4.06	4.64	5.24
1440 (24-hr)	2.69	3.36	3.92	4.82	5.51	6.25

Zone 9						
Duration (min)	**2-yr**	**5-yr**	**10-yr**	**25-yr**	**50-yr**	**100-yr**
5	0.34	0.42	0.48	0.55	0.60	0.66
10	0.53	0.65	0.73	0.84	0.92	1.00
15	0.63	0.78	0.89	1.03	1.13	1.23
30	0.84	1.07	1.23	1.44	1.60	1.75
60 (1-hr)	1.16	1.48	1.74	2.08	2.35	2.62
120 (2-hr)	1.36	1.74	2.05	2.49	2.84	3.20
180 (3-hr)	1.49	1.91	2.26	2.55	2.92	3.30
360 (6-hr)	1.72	2.19	2.58	3.14	3.61	4.10
720 (12-hr)	1.97	2.48	2.92	3.53	4.04	4.57
1080 (18-hr)	2.14	2.68	3.14	3.81	4.35	4.91
1440 (24-hr)	2.56	3.20	3.73	4.50	5.15	5.85

Zone 10						
Duration (min)	**2-yr**	**5-yr**	**10-yr**	**25-yr**	**50-yr**	**100-yr**
5	0.33	0.40	0.45	0.52	0.57	0.62
10	0.50	0.62	0.70	0.80	0.88	0.96
15	0.60	0.74	0.84	0.98	1.08	1.17
30	0.81	1.02	1.17	1.37	1.52	1.67
60 (1-hr)	1.11	1.41	1.66	1.97	2.23	2.48
120 (2-hr)	1.29	1.66	1.96	2.36	2.69	3.03
180 (3-hr)	1.42	1.82	2.15	2.43	2.78	3.14
360 (6-hr)	1.63	2.08	2.45	2.97	3.40	3.87
720 (12-hr)	1.86	2.34	2.75	3.39	3.88	4.39
1080 (18-hr)	2.02	2.54	2.97	3.60	4.11	4.65
1440 (24-hr)	2.42	3.02	3.52	4.24	4.85	5.50

Appendix C Rainfall Intensity - Duration Tables for MDOT Road Design Manual.

Figure C.1. Ten National Weather Service (NWS) zones located in Michigan and used as rainfall frequency zones.

Table C.1. RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
10.0	3.85	4.86	3.67	4.63	3.95	4.99	3.86	4.87	4.24	5.34
10.1	3.84	4.84	3.66	4.61	3.94	4.97	3.85	4.85	4.22	5.32
10.2	3.82	4.82	3.64	4.59	3.92	4.95	3.83	4.83	4.20	5.30
10.3	3.81	4.80	3.63	4.58	3.90	4.93	3.81	4.81	4.18	5.28
10.4	3.79	4.78	3.61	4.56	3.89	4.91	3.80	4.79	4.16	5.26
10.5	3.77	4.76	3.59	4.54	3.87	4.89	3.78	4.77	4.15	5.24
10.6	3.76	4.74	3.58	4.52	3.85	4.87	3.76	4.75	4.13	5.21
10.7	3.74	4.72	3.56	4.50	3.84	4.85	3.75	4.73	4.11	5.19
10.8	3.72	4.71	3.55	4.48	3.82	4.83	3.73	4.71	4.09	5.17
10.9	3.71	4.69	3.53	4.47	3.80	4.81	3.72	4.70	4.08	5.15
11.0	3.69	4.67	3.52	4.45	3.79	4.79	3.70	4.68	4.06	5.13
11.1	3.68	4.65	3.50	4.43	3.77	4.77	3.68	4.66	4.04	5.11
11.2	3.66	4.63	3.49	4.41	3.76	4.75	3.67	4.64	4.02	5.09
11.3	3.64	4.61	3.47	4.39	3.74	4.73	3.65	4.62	4.01	5.07
11.4	3.63	4.59	3.46	4.38	3.72	4.71	3.64	4.60	3.99	5.05
11.5	3.61	4.57	3.44	4.36	3.71	4.69	3.62	4.58	3.97	5.03
11.6	3.60	4.55	3.43	4.34	3.69	4.67	3.60	4.56	3.95	5.01
11.7	3.58	4.54	3.41	4.32	3.68	4.65	3.59	4.54	3.94	4.99
11.8	3.57	4.52	3.40	4.30	3.66	4.63	3.57	4.53	3.92	4.97
11.9	3.55	4.50	3.38	4.29	3.64	4.62	3.56	4.51	3.90	4.95
12.0	3.54	4.48	3.37	4.27	3.63	4.60	3.54	4.49	3.89	4.93
12.1	3.52	4.46	3.36	4.25	3.61	4.58	3.53	4.47	3.87	4.91
12.2	3.51	4.45	3.34	4.24	3.60	4.56	3.51	4.45	3.85	4.89
12.3	3.49	4.43	3.33	4.22	3.58	4.54	3.50	4.43	3.84	4.87
12.4	3.48	4.41	3.31	4.20	3.57	4.52	3.48	4.42	3.82	4.85
12.5	3.46	4.39	3.30	4.18	3.55	4.51	3.47	4.40	3.80	4.83
12.6	3.45	4.37	3.28	4.17	3.54	4.49	3.45	4.38	3.79	4.81
12.7	3.43	4.36	3.27	4.15	3.52	4.47	3.44	4.36	3.77	4.79
12.8	3.42	4.34	3.26	4.13	3.51	4.45	3.42	4.35	3.76	4.77
12.9	3.40	4.32	3.24	4.12	3.49	4.43	3.41	4.33	3.74	4.75
13.0	3.39	4.30	3.23	4.10	3.48	4.41	3.39	4.31	3.72	4.73
13.1	3.37	4.29	3.21	4.08	3.46	4.40	3.38	4.29	3.71	4.71
13.2	3.36	4.27	3.20	4.07	3.45	4.38	3.36	4.28	3.69	4.69
13.3	3.34	4.25	3.19	4.05	3.43	4.36	3.35	4.26	3.68	4.67
13.4	3.33	4.23	3.17	4.03	3.42	4.34	3.34	4.24	3.66	4.65
13.5	3.32	4.22	3.16	4.02	3.40	4.33	3.32	4.22	3.64	4.63
13.6	3.30	4.20	3.15	4.00	3.39	4.31	3.31	4.21	3.63	4.61
13.7	3.29	4.18	3.13	3.98	3.37	4.29	3.29	4.19	3.61	4.60
13.8	3.27	4.17	3.12	3.97	3.36	4.27	3.28	4.17	3.60	4.58
13.9	3.26	4.15	3.10	3.95	3.34	4.26	3.26	4.16	3.58	4.56

Table C.1 (continued). RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
14.0	3.24	4.13	3.09	3.94	3.33	4.24	3.25	4.14	3.57	4.54
14.1	3.23	4.11	3.08	3.92	3.32	4.22	3.24	4.12	3.55	4.52
14.2	3.22	4.10	3.06	3.90	3.30	4.20	3.22	4.10	3.54	4.50
14.3	3.20	4.08	3.05	3.89	3.29	4.19	3.21	4.09	3.52	4.49
14.4	3.19	4.06	3.04	3.87	3.27	4.17	3.19	4.07	3.51	4.47
14.5	3.18	4.05	3.03	3.86	3.26	4.15	3.18	4.05	3.49	4.45
14.6	3.16	4.03	3.01	3.84	3.24	4.14	3.17	4.04	3.47	4.43
14.7	3.15	4.02	3.00	3.83	3.23	4.12	3.15	4.02	3.46	4.41
14.8	3.13	4.00	2.99	3.81	3.22	4.10	3.14	4.01	3.45	4.39
14.9	3.12	3.98	2.97	3.79	3.20	4.09	3.13	3.99	3.43	4.38
15.0	3.11	3.97	2.96	3.78	3.19	4.07	3.11	3.97	3.42	4.36
15.1	3.10	3.96	2.95	3.77	3.18	4.06	3.11	3.96	3.41	4.35
15.2	3.09	3.95	2.95	3.76	3.17	4.05	3.10	3.95	3.40	4.34
15.3	3.09	3.94	2.94	3.75	3.17	4.04	3.09	3.95	3.39	4.33
15.4	3.08	3.93	2.93	3.74	3.16	4.03	3.08	3.94	3.38	4.32
15.5	3.07	3.92	2.92	3.74	3.15	4.02	3.08	3.93	3.37	4.31
15.6	3.06	3.91	2.92	3.73	3.14	4.01	3.07	3.92	3.37	4.30
15.7	3.06	3.90	2.91	3.72	3.14	4.00	3.06	3.91	3.36	4.29
15.8	3.05	3.89	2.90	3.71	3.13	4.00	3.05	3.90	3.35	4.28
15.9	3.04	3.89	2.90	3.70	3.12	3.99	3.05	3.89	3.34	4.27
16.0	3.03	3.88	2.89	3.69	3.11	3.98	3.04	3.88	3.33	4.26
16.1	3.03	3.87	2.88	3.68	3.10	3.97	3.03	3.87	3.33	4.25
16.2	3.02	3.86	2.88	3.68	3.10	3.96	3.02	3.86	3.32	4.24
16.3	3.01	3.85	2.87	3.67	3.09	3.95	3.02	3.86	3.31	4.23
16.4	3.00	3.84	2.86	3.66	3.08	3.94	3.01	3.85	3.30	4.22
16.5	3.00	3.83	2.85	3.65	3.07	3.93	3.00	3.84	3.29	4.21
16.6	2.99	3.82	2.85	3.64	3.07	3.92	2.99	3.83	3.28	4.20
16.7	2.98	3.81	2.84	3.63	3.06	3.91	2.99	3.82	3.28	4.19
16.8	2.97	3.81	2.83	3.62	3.05	3.90	2.98	3.81	3.27	4.18
16.9	2.97	3.80	2.83	3.62	3.04	3.89	2.97	3.80	3.26	4.17
17.0	2.96	3.79	2.82	3.61	3.04	3.89	2.96	3.79	3.25	4.16
17.1	2.95	3.78	2.81	3.60	3.03	3.88	2.96	3.78	3.24	4.15
17.2	2.95	3.77	2.81	3.59	3.02	3.87	2.95	3.78	3.24	4.14
17.3	2.94	3.76	2.80	3.58	3.01	3.86	2.94	3.77	3.23	4.13
17.4	2.93	3.75	2.79	3.57	3.01	3.85	2.94	3.76	3.22	4.12
17.5	2.92	3.74	2.79	3.57	3.00	3.84	2.93	3.75	3.21	4.11
17.6	2.92	3.74	2.78	3.56	2.99	3.83	2.92	3.74	3.21	4.10
17.7	2.91	3.73	2.77	3.55	2.99	3.82	2.91	3.73	3.20	4.10
17.8	2.90	3.72	2.76	3.54	2.98	3.81	2.91	3.72	3.19	4.09
17.9	2.90	3.71	2.76	3.53	2.97	3.81	2.90	3.72	3.18	4.08

Table C.1 (continued). RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
18.0	2.89	3.70	2.75	3.53	2.96	3.80	2.89	3.71	3.17	4.07
18.1	2.88	3.69	2.74	3.52	2.96	3.79	2.89	3.70	3.17	4.06
18.2	2.87	3.68	2.74	3.51	2.95	3.78	2.88	3.69	3.16	4.05
18.3	2.87	3.68	2.73	3.50	2.94	3.77	2.87	3.68	3.15	4.04
18.4	2.86	3.67	2.72	3.49	2.93	3.76	2.86	3.67	3.14	4.03
18.5	2.85	3.66	2.72	3.48	2.93	3.75	2.86	3.66	3.14	4.02
18.6	2.85	3.65	2.71	3.48	2.92	3.74	2.85	3.66	3.13	4.01
18.7	2.84	3.64	2.70	3.47	2.91	3.74	2.84	3.65	3.12	4.00
18.8	2.83	3.63	2.70	3.46	2.91	3.73	2.84	3.64	3.11	3.99
18.9	2.83	3.63	2.69	3.45	2.90	3.72	2.83	3.63	3.11	3.98
19.0	2.82	3.62	2.68	3.44	2.89	3.71	2.82	3.62	3.10	3.97
19.1	2.81	3.61	2.68	3.44	2.88	3.70	2.82	3.61	3.09	3.96
19.2	2.81	3.60	2.67	3.43	2.88	3.69	2.81	3.61	3.08	3.96
19.3	2.80	3.59	2.67	3.42	2.87	3.68	2.80	3.60	3.08	3.95
19.4	2.79	3.58	2.66	3.41	2.86	3.68	2.80	3.59	3.07	3.94
19.5	2.79	3.58	2.65	3.40	2.86	3.67	2.79	3.58	3.06	3.93
19.6	2.78	3.57	2.65	3.40	2.85	3.66	2.78	3.57	3.05	3.92
19.7	2.77	3.56	2.64	3.39	2.84	3.65	2.78	3.56	3.05	3.91
19.8	2.77	3.55	2.63	3.38	2.84	3.64	2.77	3.56	3.04	3.90
19.9	2.76	3.54	2.63	3.37	2.83	3.63	2.76	3.55	3.03	3.89
20.0	2.75	3.53	2.62	3.37	2.82	3.62	2.76	3.54	3.02	3.88
20.1	2.74	3.53	2.61	3.36	2.81	3.62	2.75	3.53	3.02	3.87
20.2	2.74	3.52	2.61	3.35	2.81	3.61	2.74	3.52	3.01	3.87
20.3	2.73	3.51	2.60	3.34	2.80	3.60	2.74	3.51	3.00	3.86
20.4	2.72	3.50	2.59	3.33	2.79	3.59	2.73	3.51	2.99	3.85
20.5	2.72	3.49	2.59	3.33	2.79	3.58	2.72	3.50	2.99	3.84
20.6	2.71	3.49	2.58	3.32	2.78	3.57	2.72	3.49	2.98	3.83
20.7	2.71	3.48	2.58	3.31	2.77	3.57	2.71	3.48	2.97	3.82
20.8	2.70	3.47	2.57	3.30	2.77	3.56	2.70	3.47	2.96	3.81
20.9	2.69	3.46	2.56	3.30	2.76	3.55	2.70	3.47	2.96	3.80
21.0	2.69	3.45	2.56	3.29	2.75	3.54	2.69	3.46	2.95	3.79
21.1	2.68	3.45	2.55	3.28	2.75	3.53	2.68	3.45	2.94	3.79
21.2	2.67	3.44	2.54	3.27	2.74	3.52	2.68	3.44	2.94	3.78
21.3	2.67	3.43	2.54	3.27	2.73	3.52	2.67	3.43	2.93	3.77
21.4	2.66	3.42	2.53	3.26	2.73	3.51	2.66	3.43	2.92	3.76
21.5	2.65	3.41	2.53	3.25	2.72	3.50	2.66	3.42	2.91	3.75
21.6	2.65	3.41	2.52	3.24	2.71	3.49	2.65	3.41	2.91	3.74
21.7	2.64	3.40	2.51	3.24	2.71	3.48	2.64	3.40	2.90	3.73
21.8	2.63	3.39	2.51	3.23	2.70	3.48	2.64	3.39	2.89	3.73
21.9	2.63	3.38	2.50	3.22	2.69	3.47	2.63	3.39	2.89	3.72

Table C.1 (continued). RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
22.0	2.62	3.38	2.49	3.21	2.69	3.46	2.62	3.38	2.88	3.71
22.1	2.61	3.37	2.49	3.21	2.68	3.45	2.62	3.37	2.87	3.70
22.2	2.61	3.36	2.48	3.20	2.67	3.44	2.61	3.36	2.87	3.69
22.3	2.60	3.35	2.48	3.19	2.67	3.44	2.60	3.36	2.86	3.68
22.4	2.60	3.34	2.47	3.18	2.66	3.43	2.60	3.35	2.85	3.67
22.5	2.59	3.34	2.46	3.18	2.65	3.42	2.59	3.34	2.84	3.67
22.6	2.58	3.33	2.46	3.17	2.65	3.41	2.59	3.33	2.84	3.66
22.7	2.58	3.32	2.45	3.16	2.64	3.40	2.58	3.32	2.83	3.65
22.8	2.57	3.31	2.45	3.15	2.63	3.40	2.57	3.32	2.82	3.64
22.9	2.56	3.31	2.44	3.15	2.63	3.39	2.57	3.31	2.82	3.63
23.0	2.56	3.30	2.43	3.14	2.62	3.38	2.56	3.30	2.81	3.62
23.1	2.55	3.29	2.43	3.13	2.61	3.37	2.55	3.29	2.80	3.61
23.2	2.55	3.28	2.42	3.13	2.61	3.36	2.55	3.29	2.80	3.61
23.3	2.54	3.28	2.42	3.12	2.60	3.36	2.54	3.28	2.79	3.60
23.4	2.53	3.27	2.41	3.11	2.60	3.35	2.54	3.27	2.78	3.59
23.5	2.53	3.26	2.41	3.10	2.59	3.34	2.53	3.26	2.78	3.58
23.6	2.52	3.25	2.40	3.10	2.58	3.33	2.52	3.26	2.77	3.57
23.7	2.51	3.25	2.39	3.09	2.58	3.33	2.52	3.25	2.76	3.57
23.8	2.51	3.24	2.39	3.08	2.57	3.32	2.51	3.24	2.76	3.56
23.9	2.50	3.23	2.38	3.07	2.56	3.31	2.50	3.23	2.75	3.55
24.0	2.50	3.22	2.38	3.07	2.56	3.30	2.50	3.23	2.74	3.54
24.1	2.49	3.22	2.37	3.06	2.55	3.29	2.49	3.22	2.74	3.53
24.2	2.48	3.21	2.36	3.05	2.55	3.29	2.49	3.21	2.73	3.52
24.3	2.48	3.20	2.36	3.05	2.54	3.28	2.48	3.20	2.72	3.52
24.4	2.47	3.19	2.35	3.04	2.53	3.27	2.47	3.20	2.72	3.51
24.5	2.47	3.19	2.35	3.03	2.53	3.26	2.47	3.19	2.71	3.50
24.6	2.46	3.18	2.34	3.03	2.52	3.26	2.46	3.18	2.70	3.49
24.7	2.45	3.17	2.34	3.02	2.51	3.25	2.46	3.17	2.70	3.48
24.8	2.45	3.16	2.33	3.01	2.51	3.24	2.45	3.17	2.69	3.48
24.9	2.44	3.16	2.32	3.00	2.50	3.23	2.44	3.16	2.68	3.47
25.0	2.44	3.15	2.32	3.00	2.50	3.23	2.44	3.15	2.68	3.46
25.1	2.43	3.14	2.31	2.99	2.49	3.22	2.43	3.15	2.67	3.45
25.2	2.42	3.14	2.31	2.98	2.48	3.21	2.43	3.14	2.66	3.44
25.3	2.42	3.13	2.30	2.98	2.48	3.20	2.42	3.13	2.66	3.44
25.4	2.41	3.12	2.30	2.97	2.47	3.20	2.41	3.12	2.65	3.43
25.5	2.41	3.11	2.29	2.96	2.47	3.19	2.41	3.12	2.64	3.42
25.6	2.40	3.11	2.28	2.96	2.46	3.18	2.40	3.11	2.64	3.41
25.7	2.39	3.10	2.28	2.95	2.45	3.17	2.40	3.10	2.63	3.40
25.8	2.39	3.09	2.27	2.94	2.45	3.17	2.39	3.09	2.62	3.40
25.9	2.38	3.08	2.27	2.94	2.44	3.16	2.39	3.09	2.62	3.39

Table C.1 (continued). RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
26.0	2.38	3.08	2.26	2.93	2.44	3.15	2.38	3.08	2.61	3.38
26.1	2.37	3.07	2.26	2.92	2.43	3.15	2.37	3.07	2.60	3.37
26.2	2.37	3.06	2.25	2.92	2.42	3.14	2.37	3.07	2.60	3.37
26.3	2.36	3.06	2.25	2.91	2.42	3.13	2.36	3.06	2.59	3.36
26.4	2.35	3.05	2.24	2.90	2.41	3.12	2.36	3.05	2.59	3.35
26.5	2.35	3.04	2.23	2.90	2.41	3.12	2.35	3.05	2.58	3.34
26.6	2.34	3.04	2.23	2.89	2.40	3.11	2.34	3.04	2.57	3.33
26.7	2.34	3.03	2.22	2.88	2.39	3.10	2.34	3.03	2.57	3.33
26.8	2.33	3.02	2.22	2.88	2.39	3.09	2.33	3.02	2.56	3.32
26.9	2.33	3.01	2.21	2.87	2.38	3.09	2.33	3.02	2.55	3.31
27.0	2.32	3.01	2.21	2.86	2.38	3.08	2.32	3.01	2.55	3.30
27.1	2.31	3.00	2.20	2.86	2.37	3.07	2.32	3.00	2.54	3.30
27.2	2.31	2.99	2.20	2.85	2.36	3.07	2.31	3.00	2.54	3.29
27.3	2.30	2.99	2.19	2.84	2.36	3.06	2.31	2.99	2.53	3.28
27.4	2.30	2.98	2.19	2.84	2.35	3.05	2.30	2.98	2.52	3.27
27.5	2.29	2.97	2.18	2.83	2.35	3.04	2.29	2.98	2.52	3.27
27.6	2.29	2.97	2.18	2.82	2.34	3.04	2.29	2.97	2.51	3.26
27.7	2.28	2.96	2.17	2.82	2.34	3.03	2.28	2.96	2.51	3.25
27.8	2.28	2.95	2.16	2.81	2.33	3.02	2.28	2.96	2.50	3.24
27.9	2.27	2.95	2.16	2.80	2.32	3.02	2.27	2.95	2.49	3.24
28.0	2.26	2.94	2.15	2.80	2.32	3.01	2.27	2.94	2.49	3.23
28.1	2.26	2.93	2.15	2.79	2.31	3.00	2.26	2.93	2.48	3.22
28.2	2.25	2.93	2.14	2.78	2.31	3.00	2.26	2.93	2.47	3.21
28.3	2.25	2.92	2.14	2.78	2.30	2.99	2.25	2.92	2.47	3.21
28.4	2.24	2.91	2.13	2.77	2.30	2.98	2.24	2.91	2.46	3.20
28.5	2.24	2.91	2.13	2.76	2.29	2.97	2.24	2.91	2.46	3.19
28.6	2.23	2.90	2.12	2.76	2.28	2.97	2.23	2.90	2.45	3.18
28.7	2.23	2.89	2.12	2.75	2.28	2.96	2.23	2.89	2.44	3.18
28.8	2.22	2.89	2.11	2.75	2.27	2.95	2.22	2.89	2.44	3.17
28.9	2.22	2.88	2.11	2.74	2.27	2.95	2.22	2.88	2.43	3.16
29.0	2.21	2.87	2.10	2.73	2.26	2.94	2.21	2.87	2.43	3.15
29.1	2.20	2.87	2.10	2.73	2.26	2.93	2.21	2.87	2.42	3.15
29.2	2.20	2.86	2.09	2.72	2.25	2.93	2.20	2.86	2.41	3.14
29.3	2.19	2.85	2.09	2.71	2.25	2.92	2.20	2.85	2.41	3.13
29.4	2.19	2.85	2.08	2.71	2.24	2.91	2.19	2.85	2.40	3.13
29.5	2.18	2.84	2.08	2.70	2.23	2.91	2.18	2.84	2.40	3.12
29.6	2.18	2.83	2.07	2.69	2.23	2.90	2.18	2.83	2.39	3.11
29.7	2.17	2.83	2.07	2.69	2.22	2.89	2.17	2.83	2.39	3.10
29.8	2.17	2.82	2.06	2.68	2.22	2.89	2.17	2.82	2.38	3.10
29.9	2.16	2.81	2.06	2.68	2.21	2.88	2.16	2.82	2.37	3.09

Table C.1 (continued). RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 0.2 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
30.0	2.16	2.81	2.05	2.67	2.21	2.87	2.16	2.81	2.37	3.08
30.2	2.15	2.80	2.05	2.66	2.20	2.87	2.15	2.80	2.36	3.08
30.4	2.15	2.80	2.04	2.66	2.20	2.86	2.15	2.80	2.36	3.07
30.6	2.14	2.79	2.04	2.66	2.19	2.86	2.14	2.79	2.35	3.06
30.8	2.14	2.78	2.03	2.65	2.19	2.85	2.14	2.79	2.35	3.06
31.0	2.13	2.78	2.03	2.65	2.18	2.84	2.13	2.78	2.34	3.05
31.2	2.13	2.77	2.02	2.64	2.18	2.84	2.13	2.78	2.34	3.05
31.4	2.12	2.77	2.02	2.64	2.17	2.83	2.12	2.77	2.33	3.04
31.6	2.12	2.76	2.01	2.63	2.17	2.83	2.12	2.76	2.32	3.04
31.8	2.11	2.76	2.01	2.63	2.16	2.82	2.11	2.76	2.32	3.03
32.0	2.11	2.75	2.00	2.62	2.16	2.82	2.11	2.75	2.31	3.02
32.2	2.10	2.74	2.00	2.62	2.15	2.81	2.10	2.75	2.31	3.02
32.4	2.10	2.74	2.00	2.61	2.15	2.81	2.10	2.74	2.30	3.01
32.6	2.09	2.73	1.99	2.61	2.14	2.80	2.09	2.74	2.30	3.01
32.8	2.09	2.73	1.99	2.60	2.14	2.79	2.09	2.73	2.29	3.00
33.0	2.08	2.72	1.98	2.60	2.13	2.79	2.08	2.73	2.29	2.99
33.2	2.08	2.72	1.98	2.59	2.13	2.78	2.08	2.72	2.28	2.99
33.4	2.07	2.71	1.97	2.59	2.12	2.78	2.07	2.72	2.28	2.98
33.6	2.07	2.71	1.97	2.58	2.12	2.77	2.07	2.71	2.27	2.98
33.8	2.06	2.70	1.96	2.58	2.11	2.77	2.06	2.71	2.27	2.97
34.0	2.06	2.69	1.96	2.57	2.11	2.76	2.06	2.70	2.26	2.97
34.2	2.06	2.69	1.95	2.57	2.10	2.76	2.05	2.69	2.26	2.96
34.4	2.05	2.68	1.95	2.56	2.10	2.75	2.05	2.69	2.25	2.95
34.6	2.05	2.68	1.95	2.56	2.09	2.74	2.05	2.68	2.24	2.95
34.8	2.04	2.67	1.94	2.55	2.09	2.74	2.04	2.68	2.24	2.94
35.0	2.04	2.67	1.94	2.55	2.08	2.73	2.04	2.67	2.23	2.94
35.2	2.03	2.66	1.93	2.54	2.08	2.73	2.03	2.67	2.23	2.93
35.4	2.03	2.66	1.93	2.54	2.07	2.72	2.03	2.66	2.22	2.93
35.6	2.02	2.65	1.92	2.53	2.07	2.72	2.02	2.66	2.22	2.92
35.8	2.02	2.65	1.92	2.53	2.06	2.71	2.02	2.65	2.21	2.91
36.0	2.01	2.64	1.91	2.53	2.06	2.71	2.01	2.65	2.21	2.91
36.2	2.01	2.64	1.91	2.52	2.05	2.70	2.01	2.64	2.20	2.90
36.4	2.00	2.63	1.91	2.52	2.05	2.70	2.00	2.64	2.20	2.90
36.6	2.00	2.62	1.90	2.51	2.04	2.69	2.00	2.63	2.19	2.89
36.8	2.00	2.62	1.90	2.51	2.04	2.69	1.99	2.63	2.19	2.89
37.0	1.99	2.61	1.89	2.50	2.03	2.68	1.99	2.62	2.18	2.88
37.2	1.99	2.61	1.89	2.50	2.03	2.67	1.98	2.62	2.18	2.88
37.4	1.98	2.60	1.88	2.49	2.02	2.67	1.98	2.61	2.17	2.87
37.6	1.98	2.60	1.88	2.49	2.02	2.66	1.98	2.61	2.17	2.86
37.8	1.97	2.59	1.88	2.48	2.01	2.66	1.97	2.60	2.16	2.86

Table C.1 (continued). RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 0.5 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
38.0	1.97	2.59	1.87	2.48	2.01	2.65	1.97	2.60	2.16	2.85
38.5	1.96	2.57	1.86	2.47	2.00	2.64	1.95	2.58	2.15	2.84
39.0	1.95	2.56	1.85	2.46	1.98	2.63	1.94	2.57	2.13	2.83
39.5	1.93	2.55	1.84	2.44	1.97	2.61	1.93	2.56	2.12	2.81
40.0	1.92	2.54	1.83	2.43	1.96	2.60	1.92	2.54	2.11	2.80
40.5	1.91	2.52	1.82	2.42	1.95	2.59	1.91	2.53	2.10	2.79
41.0	1.90	2.51	1.81	2.41	1.94	2.58	1.90	2.52	2.08	2.77
41.5	1.89	2.50	1.80	2.40	1.93	2.56	1.89	2.51	2.07	2.76
42.0	1.88	2.48	1.79	2.39	1.92	2.55	1.88	2.49	2.06	2.75
42.5	1.87	2.47	1.78	2.38	1.90	2.54	1.87	2.48	2.05	2.73
43.0	1.86	2.46	1.77	2.37	1.89	2.53	1.85	2.47	2.04	2.72
43.5	1.85	2.45	1.76	2.36	1.88	2.51	1.84	2.46	2.02	2.71
44.0	1.84	2.43	1.75	2.34	1.87	2.50	1.83	2.45	2.01	2.69
44.5	1.83	2.42	1.74	2.33	1.86	2.49	1.82	2.43	2.00	2.68
45.0	1.82	2.41	1.73	2.32	1.85	2.48	1.81	2.42	1.99	2.67
45.5	1.81	2.40	1.72	2.31	1.84	2.46	1.80	2.41	1.98	2.65
46.0	1.80	2.39	1.71	2.30	1.83	2.45	1.79	2.40	1.97	2.64
46.5	1.79	2.37	1.70	2.29	1.82	2.44	1.78	2.39	1.95	2.63
47.0	1.78	2.36	1.69	2.28	1.80	2.43	1.77	2.37	1.94	2.62
47.5	1.77	2.35	1.68	2.27	1.79	2.42	1.76	2.36	1.93	2.60
48.0	1.76	2.34	1.67	2.26	1.78	2.40	1.75	2.35	1.92	2.59
48.5	1.75	2.33	1.66	2.25	1.77	2.39	1.74	2.34	1.91	2.58
49.0	1.74	2.31	1.65	2.24	1.76	2.38	1.73	2.33	1.90	2.57
49.5	1.73	2.30	1.64	2.23	1.75	2.37	1.72	2.32	1.89	2.55
50.0	1.72	2.29	1.63	2.22	1.74	2.36	1.71	2.31	1.88	2.54
50.5	1.71	2.28	1.62	2.21	1.73	2.34	1.70	2.29	1.87	2.53
51.0	1.70	2.27	1.61	2.20	1.72	2.33	1.69	2.28	1.86	2.52
51.5	1.69	2.26	1.60	2.19	1.71	2.32	1.68	2.27	1.84	2.51
52.0	1.68	2.24	1.59	2.18	1.70	2.31	1.67	2.26	1.83	2.49
52.5	1.67	2.23	1.58	2.17	1.69	2.30	1.66	2.25	1.82	2.48
53.0	1.66	2.22	1.58	2.16	1.68	2.29	1.65	2.24	1.81	2.47
53.5	1.65	2.21	1.57	2.15	1.67	2.28	1.64	2.23	1.80	2.46
54.0	1.64	2.20	1.56	2.14	1.66	2.26	1.63	2.22	1.79	2.45
54.5	1.63	2.19	1.55	2.13	1.65	2.25	1.62	2.21	1.78	2.43
55.0	1.62	2.18	1.54	2.12	1.64	2.24	1.61	2.19	1.77	2.42
55.5	1.61	2.17	1.53	2.11	1.63	2.23	1.60	2.18	1.76	2.41
56.0	1.60	2.15	1.52	2.10	1.62	2.22	1.59	2.17	1.75	2.40
56.5	1.59	2.14	1.51	2.09	1.61	2.21	1.58	2.16	1.74	2.39
57.0	1.58	2.13	1.50	2.08	1.60	2.20	1.58	2.15	1.73	2.38
57.5	1.57	2.12	1.50	2.07	1.59	2.19	1.57	2.14	1.72	2.37

Table C.1 (continued). RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 1.0 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
58.0	1.57	2.11	1.49	2.06	1.58	2.18	1.56	2.13	1.71	2.35
59.0	1.55	2.09	1.47	2.04	1.57	2.15	1.54	2.11	1.69	2.33
60.0	1.53	2.07	1.45	2.02	1.55	2.13	1.52	2.09	1.67	2.31
61.0	1.52	2.05	1.44	2.00	1.53	2.12	1.51	2.07	1.66	2.29
62.0	1.50	2.03	1.43	1.99	1.52	2.10	1.49	2.05	1.64	2.27
63.0	1.49	2.02	1.42	1.97	1.51	2.08	1.48	2.04	1.63	2.25
64.0	1.48	2.00	1.41	1.96	1.50	2.07	1.47	2.02	1.62	2.23
65.0	1.46	1.98	1.39	1.94	1.48	2.05	1.46	2.00	1.60	2.22
66.0	1.45	1.97	1.38	1.92	1.47	2.03	1.44	1.99	1.59	2.20
67.0	1.44	1.95	1.37	1.91	1.46	2.02	1.43	1.97	1.57	2.18
68.0	1.43	1.93	1.36	1.89	1.45	2.00	1.42	1.95	1.56	2.16
69.0	1.41	1.92	1.35	1.88	1.43	1.98	1.41	1.94	1.55	2.14
70.0	1.40	1.90	1.34	1.86	1.42	1.97	1.39	1.92	1.54	2.13
71.0	1.39	1.89	1.32	1.85	1.41	1.95	1.38	1.90	1.52	2.11
72.0	1.38	1.87	1.31	1.83	1.40	1.94	1.37	1.89	1.51	2.09
73.0	1.36	1.85	1.30	1.82	1.39	1.92	1.36	1.87	1.50	2.07
74.0	1.35	1.84	1.29	1.80	1.38	1.91	1.35	1.86	1.48	2.06
75.0	1.34	1.82	1.28	1.79	1.36	1.89	1.33	1.84	1.47	2.04
76.0	1.33	1.81	1.27	1.77	1.35	1.87	1.32	1.83	1.46	2.02
77.0	1.32	1.79	1.26	1.76	1.34	1.86	1.31	1.81	1.45	2.01
78.0	1.30	1.78	1.25	1.74	1.33	1.84	1.30	1.80	1.43	1.99
79.0	1.29	1.76	1.24	1.73	1.32	1.83	1.29	1.78	1.42	1.97
80.0	1.28	1.75	1.23	1.72	1.31	1.82	1.28	1.77	1.41	1.96
81.0	1.27	1.73	1.22	1.70	1.30	1.80	1.26	1.75	1.40	1.94
82.0	1.26	1.72	1.21	1.69	1.29	1.79	1.25	1.74	1.39	1.92
83.0	1.25	1.70	1.20	1.67	1.28	1.77	1.24	1.72	1.38	1.91
84.0	1.24	1.69	1.19	1.66	1.26	1.76	1.23	1.71	1.36	1.89
85.0	1.23	1.68	1.18	1.65	1.25	1.74	1.22	1.69	1.35	1.88
86.0	1.22	1.66	1.17	1.63	1.24	1.73	1.21	1.68	1.34	1.86
87.0	1.20	1.65	1.16	1.62	1.23	1.72	1.20	1.67	1.33	1.85
88.0	1.19	1.63	1.15	1.61	1.22	1.70	1.19	1.65	1.32	1.83
89.0	1.18	1.62	1.14	1.59	1.21	1.69	1.18	1.64	1.31	1.82
90.0	1.17	1.61	1.13	1.58	1.20	1.67	1.17	1.62	1.30	1.80
91.0	1.16	1.59	1.12	1.57	1.19	1.66	1.16	1.61	1.29	1.79
92.0	1.15	1.58	1.11	1.56	1.18	1.65	1.15	1.60	1.27	1.77
93.0	1.14	1.57	1.10	1.54	1.17	1.63	1.14	1.58	1.26	1.76
94.0	1.13	1.55	1.09	1.53	1.16	1.62	1.13	1.57	1.25	1.74
95.0	1.12	1.54	1.08	1.52	1.15	1.61	1.12	1.56	1.24	1.73
96.0	1.11	1.53	1.07	1.51	1.14	1.59	1.11	1.54	1.23	1.71
97.0	1.10	1.51	1.06	1.49	1.13	1.58	1.10	1.53	1.22	1.70
98.0	1.09	1.50	1.05	1.48	1.12	1.57	1.09	1.52	1.21	1.69

Table C.1 (continued). RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 2.0 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
100.0	1.07	1.48	1.04	1.46	1.11	1.54	1.07	1.49	1.19	1.66
102.0	1.05	1.45	1.02	1.43	1.09	1.52	1.05	1.47	1.17	1.63
104.0	1.04	1.43	1.00	1.41	1.07	1.50	1.03	1.44	1.15	1.60
106.0	1.02	1.40	0.98	1.39	1.05	1.47	1.02	1.42	1.13	1.58
108.0	1.00	1.38	0.97	1.36	1.03	1.45	1.00	1.40	1.11	1.55
110.0	0.98	1.36	0.95	1.34	1.02	1.42	0.98	1.37	1.09	1.53
112.0	0.97	1.33	0.94	1.32	1.00	1.40	0.96	1.35	1.08	1.50
114.0	0.95	1.31	0.92	1.30	0.98	1.38	0.95	1.33	1.06	1.48
116.0	0.93	1.29	0.90	1.28	0.97	1.36	0.93	1.31	1.04	1.45
118.0	0.92	1.27	0.89	1.26	0.95	1.34	0.91	1.28	1.02	1.43
120.0	0.90	1.25	0.87	1.24	0.93	1.31	0.90	1.26	1.01	1.41
122.0	0.89	1.23	0.87	1.22	0.92	1.30	0.89	1.25	0.99	1.39
124.0	0.88	1.22	0.86	1.21	0.92	1.28	0.88	1.23	0.98	1.37
126.0	0.87	1.20	0.85	1.19	0.91	1.26	0.87	1.21	0.97	1.35
128.0	0.86	1.19	0.84	1.17	0.90	1.25	0.86	1.20	0.96	1.33
130.0	0.85	1.17	0.83	1.16	0.89	1.23	0.85	1.18	0.95	1.32
132.0	0.85	1.16	0.82	1.14	0.88	1.22	0.84	1.17	0.95	1.30
134.0	0.84	1.14	0.81	1.13	0.87	1.20	0.84	1.15	0.94	1.28
136.0	0.83	1.13	0.81	1.11	0.86	1.18	0.83	1.14	0.93	1.27
138.0	0.82	1.11	0.80	1.10	0.85	1.17	0.82	1.12	0.92	1.25
140.0	0.81	1.10	0.79	1.09	0.84	1.15	0.81	1.11	0.91	1.23
142.0	0.80	1.08	0.78	1.07	0.83	1.14	0.80	1.09	0.90	1.22
144.0	0.79	1.07	0.77	1.06	0.83	1.12	0.79	1.08	0.89	1.20
146.0	0.79	1.06	0.77	1.04	0.82	1.11	0.79	1.07	0.88	1.19
148.0	0.78	1.04	0.76	1.03	0.81	1.10	0.78	1.05	0.87	1.17
150.0	0.77	1.03	0.75	1.02	0.80	1.08	0.77	1.04	0.86	1.16
152.0	0.76	1.02	0.74	1.00	0.79	1.07	0.76	1.03	0.85	1.14
154.0	0.76	1.01	0.74	0.99	0.78	1.05	0.75	1.01	0.84	1.13
156.0	0.75	0.99	0.73	0.98	0.78	1.04	0.75	1.00	0.84	1.11
158.0	0.74	0.98	0.72	0.96	0.77	1.03	0.74	0.99	0.83	1.10
160.0	0.73	0.97	0.71	0.95	0.76	1.01	0.73	0.97	0.82	1.08
162.0	0.72	0.96	0.71	0.94	0.75	1.00	0.72	0.96	0.81	1.07
164.0	0.72	0.94	0.70	0.93	0.74	0.99	0.72	0.95	0.80	1.06
166.0	0.71	0.93	0.69	0.92	0.74	0.97	0.71	0.94	0.79	1.04
168.0	0.70	0.92	0.69	0.90	0.73	0.96	0.70	0.92	0.79	1.03

Table C.1 (continued). RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 2.0 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
170.0	0.70	0.91	0.68	0.89	0.72	0.95	0.70	0.91	0.78	1.02
172.0	0.69	0.90	0.67	0.88	0.71	0.94	0.69	0.90	0.77	1.00
174.0	0.68	0.88	0.66	0.87	0.71	0.92	0.68	0.89	0.76	0.99
176.0	0.67	0.87	0.66	0.86	0.70	0.91	0.67	0.88	0.75	0.98
178.0	0.67	0.86	0.65	0.85	0.69	0.90	0.67	0.87	0.75	0.96
180.0	0.66	0.85	0.64	0.84	0.69	0.89	0.66	0.85	0.74	0.95
182.0	0.66	0.85	0.64	0.83	0.68	0.88	0.66	0.85	0.73	0.95
184.0	0.65	0.84	0.64	0.83	0.68	0.88	0.65	0.85	0.73	0.94
186.0	0.65	0.84	0.63	0.82	0.67	0.88	0.65	0.84	0.73	0.94
188.0	0.64	0.83	0.63	0.82	0.67	0.87	0.64	0.84	0.72	0.93
190.0	0.64	0.83	0.63	0.81	0.67	0.87	0.64	0.83	0.72	0.93
192.0	0.64	0.83	0.62	0.81	0.66	0.86	0.64	0.83	0.71	0.92
194.0	0.63	0.82	0.62	0.81	0.66	0.86	0.63	0.82	0.71	0.92
196.0	0.63	0.82	0.61	0.80	0.65	0.85	0.63	0.82	0.70	0.91
198.0	0.63	0.81	0.61	0.80	0.65	0.85	0.62	0.82	0.70	0.91
200.0	0.62	0.81	0.61	0.79	0.65	0.85	0.62	0.81	0.70	0.90
202.0	0.62	0.80	0.60	0.79	0.64	0.84	0.62	0.81	0.69	0.90
204.0	0.61	0.80	0.60	0.79	0.64	0.84	0.61	0.80	0.69	0.90
206.0	0.61	0.80	0.60	0.78	0.63	0.83	0.61	0.80	0.68	0.89
208.0	0.61	0.79	0.59	0.78	0.63	0.83	0.61	0.80	0.68	0.89
210.0	0.60	0.79	0.59	0.77	0.63	0.82	0.60	0.79	0.68	0.88
212.0	0.60	0.78	0.59	0.77	0.62	0.82	0.60	0.79	0.67	0.88
214.0	0.60	0.78	0.58	0.77	0.62	0.82	0.60	0.78	0.67	0.87
216.0	0.59	0.78	0.58	0.76	0.61	0.81	0.59	0.78	0.66	0.87
218.0	0.59	0.77	0.57	0.76	0.61	0.81	0.59	0.78	0.66	0.86
220.0	0.59	0.77	0.57	0.75	0.61	0.80	0.58	0.77	0.66	0.86
222.0	0.58	0.76	0.57	0.75	0.60	0.80	0.58	0.77	0.65	0.86
224.0	0.58	0.76	0.56	0.75	0.60	0.80	0.58	0.76	0.65	0.85
226.0	0.58	0.76	0.56	0.74	0.60	0.79	0.57	0.76	0.64	0.85
228.0	0.57	0.75	0.56	0.74	0.59	0.79	0.57	0.76	0.64	0.84
230.0	0.57	0.75	0.55	0.74	0.59	0.78	0.57	0.75	0.64	0.84
232.0	0.56	0.74	0.55	0.73	0.58	0.78	0.56	0.75	0.63	0.83
234.0	0.56	0.74	0.55	0.73	0.58	0.78	0.56	0.74	0.63	0.83
236.0	0.56	0.74	0.54	0.72	0.58	0.77	0.56	0.74	0.63	0.83
238.0	0.55	0.73	0.54	0.72	0.57	0.77	0.55	0.74	0.62	0.82
240.0	0.55	0.73	0.54	0.72	0.57	0.76	0.55	0.73	0.62	0.82

Table C.1 (continued). RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
10.0	4.26	5.37	4.09	5.16	4.42	5.58	4.40	5.54	4.19	5.28
10.1	4.24	5.35	4.07	5.14	4.41	5.56	4.38	5.52	4.17	5.26
10.2	4.22	5.33	4.05	5.11	4.39	5.53	4.36	5.50	4.15	5.24
10.3	4.21	5.31	4.04	5.09	4.37	5.51	4.34	5.48	4.14	5.22
10.4	4.19	5.29	4.02	5.07	4.35	5.49	4.32	5.45	4.12	5.20
10.5	4.17	5.26	4.00	5.05	4.33	5.47	4.30	5.43	4.10	5.18
10.6	4.15	5.24	3.99	5.03	4.31	5.45	4.28	5.41	4.08	5.16
10.7	4.13	5.22	3.97	5.01	4.29	5.42	4.26	5.39	4.06	5.13
10.8	4.12	5.20	3.95	4.99	4.27	5.40	4.25	5.37	4.05	5.11
10.9	4.10	5.18	3.93	4.97	4.26	5.38	4.23	5.34	4.03	5.09
11.0	4.08	5.16	3.92	4.95	4.24	5.36	4.21	5.32	4.01	5.07
11.1	4.06	5.14	3.90	4.93	4.22	5.34	4.19	5.30	4.00	5.05
11.2	4.05	5.12	3.88	4.91	4.20	5.31	4.17	5.28	3.98	5.03
11.3	4.03	5.10	3.87	4.89	4.18	5.29	4.16	5.26	3.96	5.01
11.4	4.01	5.08	3.85	4.87	4.17	5.27	4.14	5.24	3.94	4.99
11.5	3.99	5.05	3.83	4.85	4.15	5.25	4.12	5.21	3.93	4.97
11.6	3.98	5.03	3.82	4.83	4.13	5.23	4.10	5.19	3.91	4.95
11.7	3.96	5.01	3.80	4.81	4.11	5.21	4.08	5.17	3.89	4.93
11.8	3.94	4.99	3.79	4.79	4.09	5.19	4.07	5.15	3.88	4.91
11.9	3.93	4.97	3.77	4.77	4.08	5.17	4.05	5.13	3.86	4.89
12.0	3.91	4.95	3.75	4.76	4.06	5.14	4.03	5.11	3.84	4.87
12.1	3.89	4.93	3.74	4.74	4.04	5.12	4.02	5.09	3.83	4.85
12.2	3.88	4.91	3.72	4.72	4.02	5.10	4.00	5.07	3.81	4.83
12.3	3.86	4.89	3.70	4.70	4.01	5.08	3.98	5.05	3.79	4.81
12.4	3.84	4.87	3.69	4.68	3.99	5.06	3.96	5.03	3.78	4.79
12.5	3.83	4.85	3.67	4.66	3.97	5.04	3.95	5.01	3.76	4.77
12.6	3.81	4.83	3.66	4.64	3.96	5.02	3.93	4.99	3.74	4.75
12.7	3.79	4.81	3.64	4.62	3.94	5.00	3.91	4.97	3.73	4.73
12.8	3.78	4.79	3.63	4.60	3.92	4.98	3.90	4.95	3.71	4.71
12.9	3.76	4.78	3.61	4.59	3.91	4.96	3.88	4.93	3.70	4.69
13.0	3.74	4.76	3.60	4.57	3.89	4.94	3.86	4.91	3.68	4.68
13.1	3.73	4.74	3.58	4.55	3.87	4.92	3.85	4.89	3.66	4.66
13.2	3.71	4.72	3.56	4.53	3.86	4.90	3.83	4.87	3.65	4.64
13.3	3.70	4.70	3.55	4.51	3.84	4.88	3.81	4.85	3.63	4.62
13.4	3.68	4.68	3.53	4.49	3.82	4.86	3.80	4.83	3.62	4.60
13.5	3.66	4.66	3.52	4.48	3.81	4.84	3.78	4.81	3.60	4.58
13.6	3.65	4.64	3.50	4.46	3.79	4.82	3.76	4.79	3.59	4.56
13.7	3.63	4.62	3.49	4.44	3.77	4.80	3.75	4.77	3.57	4.54
13.8	3.62	4.60	3.47	4.42	3.76	4.78	3.73	4.75	3.56	4.53
13.9	3.60	4.59	3.46	4.40	3.74	4.76	3.72	4.73	3.54	4.51

Table C.1 (continued). RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
14.0	3.59	4.57	3.44	4.39	3.72	4.74	3.70	4.71	3.53	4.49
14.1	3.57	4.55	3.43	4.37	3.71	4.72	3.68	4.69	3.51	4.47
14.2	3.56	4.53	3.41	4.35	3.69	4.70	3.67	4.67	3.50	4.45
14.3	3.54	4.51	3.40	4.33	3.68	4.68	3.65	4.65	3.48	4.43
14.4	3.53	4.49	3.39	4.31	3.66	4.67	3.64	4.63	3.47	4.42
14.5	3.51	4.47	3.37	4.30	3.65	4.65	3.62	4.62	3.45	4.40
14.6	3.50	4.46	3.36	4.28	3.63	4.63	3.60	4.60	3.44	4.38
14.7	3.48	4.44	3.34	4.26	3.61	4.61	3.59	4.58	3.42	4.36
14.8	3.47	4.42	3.33	4.25	3.60	4.59	3.57	4.56	3.41	4.34
14.9	3.45	4.40	3.31	4.23	3.58	4.57	3.56	4.54	3.39	4.33
15.0	3.44	4.38	3.30	4.21	3.57	4.55	3.54	4.52	3.38	4.31
15.1	3.43	4.37	3.29	4.20	3.56	4.54	3.53	4.51	3.37	4.30
15.2	3.42	4.36	3.28	4.19	3.55	4.53	3.53	4.50	3.36	4.29
15.3	3.41	4.35	3.28	4.18	3.54	4.52	3.52	4.49	3.35	4.28
15.4	3.40	4.34	3.27	4.17	3.53	4.51	3.51	4.48	3.34	4.27
15.5	3.39	4.33	3.26	4.16	3.52	4.50	3.50	4.47	3.34	4.26
15.6	3.39	4.32	3.25	4.15	3.52	4.49	3.49	4.46	3.33	4.25
15.7	3.38	4.31	3.24	4.14	3.51	4.48	3.48	4.45	3.32	4.24
15.8	3.37	4.30	3.24	4.13	3.50	4.47	3.47	4.44	3.31	4.23
15.9	3.36	4.29	3.23	4.12	3.49	4.46	3.47	4.43	3.30	4.22
16.0	3.35	4.28	3.22	4.11	3.48	4.45	3.46	4.42	3.30	4.21
16.1	3.34	4.27	3.21	4.10	3.47	4.44	3.45	4.41	3.29	4.20
16.2	3.34	4.26	3.20	4.10	3.46	4.43	3.44	4.40	3.28	4.19
16.3	3.33	4.26	3.20	4.09	3.46	4.42	3.43	4.39	3.27	4.18
16.4	3.32	4.25	3.19	4.08	3.45	4.41	3.42	4.38	3.26	4.17
16.5	3.31	4.24	3.18	4.07	3.44	4.40	3.42	4.37	3.26	4.16
16.6	3.30	4.23	3.17	4.06	3.43	4.39	3.41	4.36	3.25	4.15
16.7	3.30	4.22	3.16	4.05	3.42	4.38	3.40	4.35	3.24	4.14
16.8	3.29	4.21	3.16	4.04	3.41	4.37	3.39	4.34	3.23	4.13
16.9	3.28	4.20	3.15	4.03	3.41	4.36	3.38	4.33	3.22	4.12
17.0	3.27	4.19	3.14	4.02	3.40	4.35	3.37	4.32	3.22	4.12
17.1	3.26	4.18	3.13	4.01	3.39	4.34	3.37	4.31	3.21	4.11
17.2	3.26	4.17	3.13	4.00	3.38	4.33	3.36	4.30	3.20	4.10
17.3	3.25	4.16	3.12	3.99	3.37	4.32	3.35	4.29	3.19	4.09
17.4	3.24	4.15	3.11	3.98	3.36	4.31	3.34	4.28	3.18	4.08
17.5	3.23	4.14	3.10	3.97	3.36	4.30	3.33	4.27	3.18	4.07
17.6	3.22	4.13	3.10	3.96	3.35	4.29	3.33	4.26	3.17	4.06
17.7	3.22	4.12	3.09	3.95	3.34	4.28	3.32	4.25	3.16	4.05
17.8	3.21	4.11	3.08	3.95	3.33	4.27	3.31	4.24	3.15	4.04
17.9	3.20	4.10	3.07	3.94	3.32	4.26	3.30	4.23	3.15	4.03

Table C.1 (continued). RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
18.0	3.19	4.09	3.07	3.93	3.32	4.25	3.29	4.22	3.14	4.02
18.1	3.19	4.08	3.06	3.92	3.31	4.24	3.29	4.21	3.13	4.01
18.2	3.18	4.07	3.05	3.91	3.30	4.23	3.28	4.20	3.12	4.00
18.3	3.17	4.06	3.04	3.90	3.29	4.22	3.27	4.19	3.12	3.99
18.4	3.16	4.05	3.04	3.89	3.28	4.21	3.26	4.18	3.11	3.98
18.5	3.15	4.04	3.03	3.88	3.28	4.20	3.25	4.17	3.10	3.97
18.6	3.15	4.03	3.02	3.87	3.27	4.19	3.25	4.16	3.09	3.97
18.7	3.14	4.03	3.01	3.86	3.26	4.18	3.24	4.15	3.09	3.96
18.8	3.13	4.02	3.01	3.86	3.25	4.17	3.23	4.14	3.08	3.95
18.9	3.12	4.01	3.00	3.85	3.24	4.16	3.22	4.13	3.07	3.94
19.0	3.12	4.00	2.99	3.84	3.24	4.15	3.21	4.12	3.06	3.93
19.1	3.11	3.99	2.98	3.83	3.23	4.14	3.21	4.11	3.06	3.92
19.2	3.10	3.98	2.98	3.82	3.22	4.13	3.20	4.10	3.05	3.91
19.3	3.09	3.97	2.97	3.81	3.21	4.12	3.19	4.09	3.04	3.90
19.4	3.09	3.96	2.96	3.80	3.20	4.11	3.18	4.08	3.03	3.89
19.5	3.08	3.95	2.95	3.79	3.20	4.10	3.17	4.08	3.03	3.88
19.6	3.07	3.94	2.95	3.78	3.19	4.09	3.17	4.07	3.02	3.88
19.7	3.06	3.93	2.94	3.78	3.18	4.08	3.16	4.06	3.01	3.87
19.8	3.06	3.92	2.93	3.77	3.17	4.08	3.15	4.05	3.00	3.86
19.9	3.05	3.91	2.93	3.76	3.17	4.07	3.14	4.04	3.00	3.85
20.0	3.04	3.91	2.92	3.75	3.16	4.06	3.14	4.03	2.99	3.84
20.1	3.03	3.90	2.91	3.74	3.15	4.05	3.13	4.02	2.98	3.83
20.2	3.03	3.89	2.90	3.73	3.14	4.04	3.12	4.01	2.97	3.82
20.3	3.02	3.88	2.90	3.72	3.13	4.03	3.11	4.00	2.97	3.81
20.4	3.01	3.87	2.89	3.71	3.13	4.02	3.11	3.99	2.96	3.80
20.5	3.00	3.86	2.88	3.71	3.12	4.01	3.10	3.98	2.95	3.80
20.6	3.00	3.85	2.88	3.70	3.11	4.00	3.09	3.97	2.95	3.79
20.7	2.99	3.84	2.87	3.69	3.10	3.99	3.08	3.96	2.94	3.78
20.8	2.98	3.83	2.86	3.68	3.10	3.98	3.08	3.95	2.93	3.77
20.9	2.97	3.83	2.85	3.67	3.09	3.97	3.07	3.95	2.92	3.76
21.0	2.97	3.82	2.85	3.66	3.08	3.96	3.06	3.94	2.92	3.75
21.1	2.96	3.81	2.84	3.65	3.07	3.95	3.05	3.93	2.91	3.74
21.2	2.95	3.80	2.83	3.65	3.07	3.95	3.05	3.92	2.90	3.73
21.3	2.95	3.79	2.83	3.64	3.06	3.94	3.04	3.91	2.90	3.73
21.4	2.94	3.78	2.82	3.63	3.05	3.93	3.03	3.90	2.89	3.72
21.5	2.93	3.77	2.81	3.62	3.04	3.92	3.02	3.89	2.88	3.71
21.6	2.92	3.76	2.81	3.61	3.04	3.91	3.02	3.88	2.87	3.70
21.7	2.92	3.76	2.80	3.60	3.03	3.90	3.01	3.87	2.87	3.69
21.8	2.91	3.75	2.79	3.60	3.02	3.89	3.00	3.86	2.86	3.68
21.9	2.90	3.74	2.79	3.59	3.01	3.88	2.99	3.86	2.85	3.67

Table C.1 (continued). RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
22.0	2.90	3.73	2.78	3.58	3.01	3.87	2.99	3.85	2.85	3.67
22.1	2.89	3.72	2.77	3.57	3.00	3.86	2.98	3.84	2.84	3.66
22.2	2.88	3.71	2.76	3.56	2.99	3.86	2.97	3.83	2.83	3.65
22.3	2.87	3.70	2.76	3.55	2.99	3.85	2.96	3.82	2.83	3.64
22.4	2.87	3.69	2.75	3.55	2.98	3.84	2.96	3.81	2.82	3.63
22.5	2.86	3.69	2.74	3.54	2.97	3.83	2.95	3.80	2.81	3.62
22.6	2.85	3.68	2.74	3.53	2.96	3.82	2.94	3.79	2.81	3.62
22.7	2.85	3.67	2.73	3.52	2.96	3.81	2.94	3.79	2.80	3.61
22.8	2.84	3.66	2.72	3.51	2.95	3.80	2.93	3.78	2.79	3.60
22.9	2.83	3.65	2.72	3.50	2.94	3.79	2.92	3.77	2.78	3.59
23.0	2.83	3.64	2.71	3.50	2.93	3.78	2.91	3.76	2.78	3.58
23.1	2.82	3.64	2.70	3.49	2.93	3.78	2.91	3.75	2.77	3.57
23.2	2.81	3.63	2.70	3.48	2.92	3.77	2.90	3.74	2.76	3.57
23.3	2.81	3.62	2.69	3.47	2.91	3.76	2.89	3.73	2.76	3.56
23.4	2.80	3.61	2.68	3.46	2.91	3.75	2.89	3.72	2.75	3.55
23.5	2.79	3.60	2.68	3.46	2.90	3.74	2.88	3.72	2.74	3.54
23.6	2.78	3.59	2.67	3.45	2.89	3.73	2.87	3.71	2.74	3.53
23.7	2.78	3.59	2.66	3.44	2.88	3.72	2.87	3.70	2.73	3.53
23.8	2.77	3.58	2.66	3.43	2.88	3.72	2.86	3.69	2.72	3.52
23.9	2.76	3.57	2.65	3.42	2.87	3.71	2.85	3.68	2.72	3.51
24.0	2.76	3.56	2.65	3.42	2.86	3.70	2.84	3.67	2.71	3.50
24.1	2.75	3.55	2.64	3.41	2.86	3.69	2.84	3.66	2.70	3.49
24.2	2.74	3.54	2.63	3.40	2.85	3.68	2.83	3.66	2.70	3.48
24.3	2.74	3.54	2.63	3.39	2.84	3.67	2.82	3.65	2.69	3.48
24.4	2.73	3.53	2.62	3.38	2.84	3.66	2.82	3.64	2.68	3.47
24.5	2.72	3.52	2.61	3.38	2.83	3.66	2.81	3.63	2.68	3.46
24.6	2.72	3.51	2.61	3.37	2.82	3.65	2.80	3.62	2.67	3.45
24.7	2.71	3.50	2.60	3.36	2.82	3.64	2.80	3.61	2.67	3.44
24.8	2.70	3.50	2.59	3.35	2.81	3.63	2.79	3.61	2.66	3.44
24.9	2.70	3.49	2.59	3.34	2.80	3.62	2.78	3.60	2.65	3.43
25.0	2.69	3.48	2.58	3.34	2.79	3.61	2.78	3.59	2.65	3.42
25.1	2.68	3.47	2.57	3.33	2.79	3.61	2.77	3.58	2.64	3.41
25.2	2.68	3.46	2.57	3.32	2.78	3.60	2.76	3.57	2.63	3.41
25.3	2.67	3.46	2.56	3.31	2.77	3.59	2.76	3.56	2.63	3.40
25.4	2.66	3.45	2.56	3.31	2.77	3.58	2.75	3.56	2.62	3.39
25.5	2.66	3.44	2.55	3.30	2.76	3.57	2.74	3.55	2.61	3.38
25.6	2.65	3.43	2.54	3.29	2.75	3.56	2.74	3.54	2.61	3.37
25.7	2.65	3.42	2.54	3.28	2.75	3.56	2.73	3.53	2.60	3.37
25.8	2.64	3.42	2.53	3.28	2.74	3.55	2.72	3.52	2.59	3.36
25.9	2.63	3.41	2.52	3.27	2.73	3.54	2.72	3.52	2.59	3.35

Table C.1 (continued). RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
26.0	2.63	3.40	2.52	3.26	2.73	3.53	2.71	3.51	2.58	3.34
26.1	2.62	3.39	2.51	3.25	2.72	3.52	2.70	3.50	2.58	3.34
26.2	2.61	3.38	2.51	3.25	2.71	3.51	2.70	3.49	2.57	3.33
26.3	2.61	3.38	2.50	3.24	2.71	3.51	2.69	3.48	2.56	3.32
26.4	2.60	3.37	2.49	3.23	2.70	3.50	2.68	3.47	2.56	3.31
26.5	2.59	3.36	2.49	3.22	2.69	3.49	2.68	3.47	2.55	3.30
26.6	2.59	3.35	2.48	3.22	2.69	3.48	2.67	3.46	2.54	3.30
26.7	2.58	3.35	2.48	3.21	2.68	3.47	2.66	3.45	2.54	3.29
26.8	2.58	3.34	2.47	3.20	2.67	3.47	2.66	3.44	2.53	3.28
26.9	2.57	3.33	2.46	3.19	2.67	3.46	2.65	3.43	2.53	3.27
27.0	2.56	3.32	2.46	3.19	2.66	3.45	2.64	3.43	2.52	3.27
27.1	2.56	3.31	2.45	3.18	2.65	3.44	2.64	3.42	2.51	3.26
27.2	2.55	3.31	2.45	3.17	2.65	3.43	2.63	3.41	2.51	3.25
27.3	2.54	3.30	2.44	3.16	2.64	3.43	2.62	3.40	2.50	3.24
27.4	2.54	3.29	2.43	3.16	2.64	3.42	2.62	3.40	2.50	3.24
27.5	2.53	3.28	2.43	3.15	2.63	3.41	2.61	3.39	2.49	3.23
27.6	2.53	3.28	2.42	3.14	2.62	3.40	2.61	3.38	2.48	3.22
27.7	2.52	3.27	2.42	3.13	2.62	3.39	2.60	3.37	2.48	3.21
27.8	2.51	3.26	2.41	3.13	2.61	3.39	2.59	3.36	2.47	3.21
27.9	2.51	3.25	2.40	3.12	2.60	3.38	2.59	3.36	2.47	3.20
28.0	2.50	3.25	2.40	3.11	2.60	3.37	2.58	3.35	2.46	3.19
28.1	2.49	3.24	2.39	3.10	2.59	3.36	2.57	3.34	2.45	3.18
28.2	2.49	3.23	2.39	3.10	2.58	3.36	2.57	3.33	2.45	3.18
28.3	2.48	3.22	2.38	3.09	2.58	3.35	2.56	3.33	2.44	3.17
28.4	2.48	3.22	2.37	3.08	2.57	3.34	2.55	3.32	2.44	3.16
28.5	2.47	3.21	2.37	3.08	2.57	3.33	2.55	3.31	2.43	3.16
28.6	2.46	3.20	2.36	3.07	2.56	3.32	2.54	3.30	2.42	3.15
28.7	2.46	3.19	2.36	3.06	2.55	3.32	2.54	3.29	2.42	3.14
28.8	2.45	3.19	2.35	3.05	2.55	3.31	2.53	3.29	2.41	3.13
28.9	2.45	3.18	2.35	3.05	2.54	3.30	2.52	3.28	2.41	3.13
29.0	2.44	3.17	2.34	3.04	2.53	3.29	2.52	3.27	2.40	3.12
29.1	2.43	3.16	2.33	3.03	2.53	3.29	2.51	3.26	2.39	3.11
29.2	2.43	3.16	2.33	3.03	2.52	3.28	2.51	3.26	2.39	3.10
29.3	2.42	3.15	2.32	3.02	2.52	3.27	2.50	3.25	2.38	3.10
29.4	2.42	3.14	2.32	3.01	2.51	3.26	2.49	3.24	2.38	3.09
29.5	2.41	3.14	2.31	3.01	2.50	3.26	2.49	3.23	2.37	3.08
29.6	2.40	3.13	2.31	3.00	2.50	3.25	2.48	3.23	2.37	3.08
29.7	2.40	3.12	2.30	2.99	2.49	3.24	2.47	3.22	2.36	3.07
29.8	2.39	3.11	2.29	2.98	2.49	3.23	2.47	3.21	2.35	3.06
29.9	2.39	3.11	2.29	2.98	2.48	3.23	2.46	3.20	2.35	3.06

Table C.1 (continued). RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 0.2 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
30.0	2.38	3.10	2.28	2.97	2.47	3.22	2.46	3.20	2.34	3.05
30.2	2.38	3.09	2.28	2.96	2.47	3.21	2.45	3.19	2.34	3.04
30.4	2.37	3.09	2.27	2.96	2.46	3.21	2.45	3.18	2.33	3.04
30.6	2.36	3.08	2.27	2.95	2.46	3.20	2.44	3.18	2.33	3.03
30.8	2.36	3.08	2.26	2.95	2.45	3.19	2.43	3.17	2.32	3.02
31.0	2.35	3.07	2.25	2.94	2.44	3.19	2.43	3.16	2.32	3.02
31.2	2.35	3.07	2.25	2.94	2.44	3.18	2.42	3.16	2.31	3.01
31.4	2.34	3.06	2.24	2.93	2.43	3.17	2.42	3.15	2.30	3.00
31.6	2.34	3.05	2.24	2.92	2.43	3.17	2.41	3.15	2.30	3.00
31.8	2.33	3.05	2.23	2.92	2.42	3.16	2.41	3.14	2.29	2.99
32.0	2.33	3.04	2.23	2.91	2.42	3.15	2.40	3.13	2.29	2.98
32.2	2.32	3.04	2.22	2.91	2.41	3.15	2.40	3.13	2.28	2.98
32.4	2.31	3.03	2.22	2.90	2.40	3.14	2.39	3.12	2.28	2.97
32.6	2.31	3.03	2.21	2.90	2.40	3.13	2.38	3.11	2.27	2.97
32.8	2.30	3.02	2.20	2.89	2.39	3.13	2.38	3.11	2.27	2.96
33.0	2.30	3.02	2.20	2.88	2.39	3.12	2.37	3.10	2.26	2.95
33.2	2.29	3.01	2.19	2.88	2.38	3.12	2.37	3.09	2.26	2.95
33.4	2.29	3.00	2.19	2.87	2.38	3.11	2.36	3.09	2.25	2.94
33.6	2.28	3.00	2.18	2.87	2.37	3.10	2.36	3.08	2.25	2.94
33.8	2.28	2.99	2.18	2.86	2.37	3.10	2.35	3.08	2.24	2.93
34.0	2.27	2.99	2.17	2.86	2.36	3.09	2.35	3.07	2.24	2.92
34.2	2.26	2.98	2.17	2.85	2.35	3.08	2.34	3.06	2.23	2.92
34.4	2.26	2.98	2.16	2.85	2.35	3.08	2.33	3.06	2.23	2.91
34.6	2.25	2.97	2.16	2.84	2.34	3.07	2.33	3.05	2.22	2.90
34.8	2.25	2.97	2.15	2.83	2.34	3.07	2.32	3.04	2.22	2.90
35.0	2.24	2.96	2.15	2.83	2.33	3.06	2.32	3.04	2.21	2.89
35.2	2.24	2.96	2.14	2.82	2.33	3.05	2.31	3.03	2.21	2.89
35.4	2.23	2.95	2.13	2.82	2.32	3.05	2.31	3.03	2.20	2.88
35.6	2.23	2.94	2.13	2.81	2.32	3.04	2.30	3.02	2.20	2.87
35.8	2.22	2.94	2.12	2.81	2.31	3.03	2.30	3.01	2.19	2.87
36.0	2.22	2.93	2.12	2.80	2.31	3.03	2.29	3.01	2.19	2.86
36.2	2.21	2.93	2.11	2.80	2.30	3.02	2.29	3.00	2.18	2.86
36.4	2.21	2.92	2.11	2.79	2.29	3.02	2.28	3.00	2.18	2.85
36.6	2.20	2.92	2.10	2.79	2.29	3.01	2.28	2.99	2.17	2.84
36.8	2.20	2.91	2.10	2.78	2.28	3.00	2.27	2.98	2.17	2.84
37.0	2.19	2.91	2.09	2.77	2.28	3.00	2.27	2.98	2.16	2.83
37.2	2.19	2.90	2.09	2.77	2.27	2.99	2.26	2.97	2.16	2.83
37.4	2.18	2.90	2.08	2.76	2.27	2.98	2.25	2.96	2.15	2.82
37.6	2.17	2.89	2.08	2.76	2.26	2.98	2.25	2.96	2.15	2.81
37.8	2.17	2.89	2.07	2.75	2.26	2.97	2.24	2.95	2.14	2.81

Table C.1 (continued). RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 0.5 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
38.0	2.16	2.88	2.07	2.75	2.25	2.97	2.24	2.95	2.14	2.80
38.5	2.15	2.87	2.05	2.73	2.24	2.95	2.23	2.93	2.12	2.79
39.0	2.14	2.85	2.04	2.72	2.23	2.94	2.21	2.92	2.11	2.77
39.5	2.13	2.84	2.03	2.71	2.21	2.92	2.20	2.90	2.10	2.76
40.0	2.11	2.83	2.02	2.69	2.20	2.91	2.19	2.89	2.09	2.74
40.5	2.10	2.82	2.00	2.68	2.19	2.89	2.18	2.87	2.08	2.73
41.0	2.09	2.80	1.99	2.67	2.17	2.88	2.16	2.86	2.06	2.72
41.5	2.08	2.79	1.98	2.66	2.16	2.86	2.15	2.84	2.05	2.70
42.0	2.06	2.78	1.97	2.64	2.15	2.85	2.14	2.83	2.04	2.69
42.5	2.05	2.76	1.95	2.63	2.14	2.83	2.13	2.81	2.03	2.67
43.0	2.04	2.75	1.94	2.62	2.12	2.82	2.11	2.80	2.02	2.66
43.5	2.03	2.74	1.93	2.60	2.11	2.80	2.10	2.79	2.01	2.65
44.0	2.02	2.73	1.92	2.59	2.10	2.79	2.09	2.77	1.99	2.63
44.5	2.00	2.71	1.91	2.58	2.09	2.78	2.08	2.76	1.98	2.62
45.0	1.99	2.70	1.90	2.57	2.07	2.76	2.06	2.74	1.97	2.60
45.5	1.98	2.69	1.88	2.55	2.06	2.75	2.05	2.73	1.96	2.59
46.0	1.97	2.68	1.87	2.54	2.05	2.73	2.04	2.72	1.95	2.58
46.5	1.96	2.66	1.86	2.53	2.04	2.72	2.03	2.70	1.94	2.56
47.0	1.94	2.65	1.85	2.52	2.03	2.71	2.02	2.69	1.93	2.55
47.5	1.93	2.64	1.84	2.50	2.01	2.69	2.01	2.67	1.92	2.54
48.0	1.92	2.63	1.83	2.49	2.00	2.68	1.99	2.66	1.91	2.52
48.5	1.91	2.62	1.81	2.48	1.99	2.67	1.98	2.65	1.89	2.51
49.0	1.90	2.60	1.80	2.47	1.98	2.65	1.97	2.63	1.88	2.50
49.5	1.89	2.59	1.79	2.46	1.97	2.64	1.96	2.62	1.87	2.48
50.0	1.88	2.58	1.78	2.44	1.96	2.62	1.95	2.61	1.86	2.47
50.5	1.86	2.57	1.77	2.43	1.94	2.61	1.94	2.59	1.85	2.46
51.0	1.85	2.56	1.76	2.42	1.93	2.60	1.93	2.58	1.84	2.45
51.5	1.84	2.55	1.75	2.41	1.92	2.59	1.92	2.57	1.83	2.43
52.0	1.83	2.53	1.74	2.40	1.91	2.57	1.90	2.55	1.82	2.42
52.5	1.82	2.52	1.73	2.38	1.90	2.56	1.89	2.54	1.81	2.41
53.0	1.81	2.51	1.72	2.37	1.89	2.55	1.88	2.53	1.80	2.39
53.5	1.80	2.50	1.71	2.36	1.88	2.53	1.87	2.51	1.79	2.38
54.0	1.79	2.49	1.70	2.35	1.87	2.52	1.86	2.50	1.78	2.37
54.5	1.78	2.48	1.68	2.34	1.85	2.51	1.85	2.49	1.77	2.36
55.0	1.77	2.47	1.67	2.33	1.84	2.49	1.84	2.48	1.76	2.34
55.5	1.76	2.45	1.66	2.32	1.83	2.48	1.83	2.46	1.75	2.33
56.0	1.75	2.44	1.65	2.30	1.82	2.47	1.82	2.45	1.74	2.32
56.5	1.74	2.43	1.64	2.29	1.81	2.46	1.81	2.44	1.73	2.31
57.0	1.73	2.42	1.63	2.28	1.80	2.44	1.80	2.43	1.72	2.30
57.5	1.72	2.41	1.62	2.27	1.79	2.43	1.79	2.41	1.71	2.28

Table C.1 (continued). RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 1.0 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
58.0	1.71	2.40	1.61	2.26	1.78	2.42	1.78	2.40	1.70	2.27
59.0	1.68	2.38	1.59	2.24	1.76	2.39	1.76	2.38	1.68	2.25
60.0	1.66	2.36	1.57	2.22	1.74	2.37	1.74	2.35	1.66	2.23
61.0	1.65	2.33	1.56	2.20	1.72	2.35	1.72	2.33	1.65	2.21
62.0	1.64	2.31	1.55	2.18	1.71	2.33	1.71	2.31	1.63	2.19
63.0	1.62	2.29	1.53	2.16	1.69	2.31	1.69	2.29	1.62	2.17
64.0	1.61	2.28	1.52	2.14	1.68	2.29	1.68	2.28	1.60	2.15
65.0	1.59	2.26	1.51	2.13	1.67	2.27	1.66	2.26	1.59	2.13
66.0	1.58	2.24	1.50	2.11	1.65	2.25	1.65	2.24	1.57	2.12
67.0	1.57	2.22	1.48	2.09	1.64	2.24	1.63	2.22	1.56	2.10
68.0	1.55	2.20	1.47	2.07	1.62	2.22	1.62	2.20	1.55	2.08
69.0	1.54	2.18	1.46	2.06	1.61	2.20	1.60	2.18	1.53	2.06
70.0	1.53	2.16	1.45	2.04	1.60	2.18	1.59	2.16	1.52	2.05
71.0	1.51	2.14	1.43	2.02	1.58	2.16	1.58	2.15	1.51	2.03
72.0	1.50	2.12	1.42	2.01	1.57	2.14	1.56	2.13	1.49	2.01
73.0	1.49	2.10	1.41	1.99	1.56	2.13	1.55	2.11	1.48	2.00
74.0	1.48	2.09	1.40	1.97	1.54	2.11	1.54	2.09	1.47	1.98
75.0	1.46	2.07	1.39	1.96	1.53	2.09	1.52	2.07	1.45	1.96
76.0	1.45	2.05	1.38	1.94	1.52	2.07	1.51	2.06	1.44	1.95
77.0	1.44	2.03	1.36	1.93	1.50	2.06	1.50	2.04	1.43	1.93
78.0	1.43	2.02	1.35	1.91	1.49	2.04	1.48	2.02	1.42	1.91
79.0	1.41	2.00	1.34	1.89	1.48	2.02	1.47	2.01	1.40	1.90
80.0	1.40	1.98	1.33	1.88	1.47	2.01	1.46	1.99	1.39	1.88
81.0	1.39	1.96	1.32	1.86	1.45	1.99	1.44	1.97	1.38	1.87
82.0	1.38	1.95	1.31	1.85	1.44	1.97	1.43	1.96	1.37	1.85
83.0	1.37	1.93	1.30	1.83	1.43	1.96	1.42	1.94	1.36	1.84
84.0	1.35	1.91	1.29	1.82	1.42	1.94	1.41	1.92	1.34	1.82
85.0	1.34	1.90	1.28	1.80	1.40	1.92	1.39	1.91	1.33	1.81
86.0	1.33	1.88	1.26	1.79	1.39	1.91	1.38	1.89	1.32	1.79
87.0	1.32	1.87	1.25	1.77	1.38	1.89	1.37	1.88	1.31	1.78
88.0	1.31	1.85	1.24	1.76	1.37	1.88	1.36	1.86	1.30	1.76
89.0	1.30	1.83	1.23	1.74	1.36	1.86	1.35	1.84	1.29	1.75
90.0	1.29	1.82	1.22	1.73	1.35	1.84	1.33	1.83	1.27	1.73
91.0	1.28	1.80	1.21	1.71	1.33	1.83	1.32	1.81	1.26	1.72
92.0	1.26	1.79	1.20	1.70	1.32	1.81	1.31	1.80	1.25	1.70
93.0	1.25	1.77	1.19	1.69	1.31	1.80	1.30	1.78	1.24	1.69
94.0	1.24	1.76	1.18	1.67	1.30	1.78	1.29	1.77	1.23	1.67
95.0	1.23	1.74	1.17	1.66	1.29	1.77	1.28	1.75	1.22	1.66
96.0	1.22	1.73	1.16	1.64	1.28	1.75	1.27	1.74	1.21	1.65
97.0	1.21	1.71	1.15	1.63	1.27	1.74	1.26	1.72	1.20	1.63
98.0	1.20	1.70	1.14	1.62	1.26	1.72	1.24	1.71	1.19	1.62

Table C.1 (continued). RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 2.0 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
100.0	1.18	1.67	1.12	1.59	1.24	1.70	1.22	1.68	1.17	1.59
102.0	1.16	1.64	1.11	1.56	1.21	1.67	1.20	1.65	1.15	1.57
104.0	1.14	1.61	1.09	1.54	1.19	1.64	1.18	1.63	1.13	1.54
106.0	1.12	1.58	1.07	1.51	1.17	1.61	1.16	1.60	1.11	1.51
108.0	1.10	1.56	1.05	1.49	1.15	1.59	1.14	1.57	1.09	1.49
110.0	1.08	1.53	1.03	1.46	1.13	1.56	1.12	1.55	1.07	1.46
112.0	1.06	1.50	1.02	1.44	1.11	1.53	1.10	1.52	1.05	1.44
114.0	1.05	1.48	1.00	1.42	1.10	1.51	1.08	1.49	1.03	1.42
116.0	1.03	1.45	0.98	1.39	1.08	1.48	1.06	1.47	1.01	1.39
118.0	1.01	1.43	0.97	1.37	1.06	1.46	1.04	1.44	1.00	1.37
120.0	0.99	1.40	0.95	1.35	1.04	1.44	1.03	1.42	0.98	1.35
122.0	0.98	1.38	0.94	1.33	1.03	1.42	1.02	1.40	0.97	1.33
124.0	0.97	1.37	0.93	1.31	1.02	1.40	1.01	1.39	0.96	1.31
126.0	0.96	1.35	0.92	1.30	1.01	1.38	1.00	1.37	0.95	1.30
128.0	0.95	1.33	0.91	1.28	1.00	1.37	0.98	1.35	0.94	1.28
130.0	0.94	1.31	0.90	1.26	0.99	1.35	0.97	1.33	0.93	1.27
132.0	0.93	1.30	0.89	1.24	0.98	1.33	0.96	1.32	0.92	1.25
134.0	0.92	1.28	0.88	1.23	0.97	1.32	0.95	1.30	0.91	1.23
136.0	0.92	1.26	0.87	1.21	0.96	1.30	0.94	1.28	0.90	1.22
138.0	0.91	1.25	0.86	1.20	0.95	1.28	0.94	1.27	0.89	1.20
140.0	0.90	1.23	0.86	1.18	0.94	1.27	0.93	1.25	0.88	1.19
142.0	0.89	1.21	0.85	1.16	0.93	1.25	0.92	1.24	0.87	1.17
144.0	0.88	1.20	0.84	1.15	0.92	1.24	0.91	1.22	0.86	1.16
146.0	0.87	1.18	0.83	1.13	0.91	1.22	0.90	1.21	0.85	1.15
148.0	0.86	1.17	0.82	1.12	0.90	1.21	0.89	1.19	0.85	1.13
150.0	0.85	1.15	0.81	1.10	0.89	1.19	0.88	1.18	0.84	1.12
152.0	0.84	1.13	0.80	1.09	0.88	1.18	0.87	1.16	0.83	1.10
154.0	0.83	1.12	0.79	1.07	0.87	1.16	0.86	1.15	0.82	1.09
156.0	0.83	1.11	0.79	1.06	0.86	1.15	0.85	1.13	0.81	1.08
158.0	0.82	1.09	0.78	1.05	0.86	1.13	0.84	1.12	0.80	1.06
160.0	0.81	1.08	0.77	1.03	0.85	1.12	0.83	1.10	0.80	1.05
162.0	0.80	1.06	0.76	1.02	0.84	1.10	0.83	1.09	0.79	1.04
164.0	0.79	1.05	0.75	1.01	0.83	1.09	0.82	1.08	0.78	1.02
166.0	0.78	1.03	0.75	0.99	0.82	1.08	0.81	1.06	0.77	1.01
168.0	0.78	1.02	0.74	0.98	0.81	1.06	0.80	1.05	0.76	1.00

Table C.1 (continued). RAINFALL INTENSITY - DURATION TABLES

TIME INTERVAL ON THIS SHEET = 2.0 MINUTES
Rainfall Intensity given in inches per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
170.0	0.77	1.01	0.73	0.97	0.80	1.05	0.79	1.04	0.76	0.99
172.0	0.76	0.99	0.72	0.95	0.80	1.04	0.78	1.02	0.75	0.97
174.0	0.75	0.98	0.72	0.94	0.79	1.02	0.78	1.01	0.74	0.96
176.0	0.74	0.97	0.71	0.93	0.78	1.01	0.77	1.00	0.73	0.95
178.0	0.74	0.96	0.70	0.92	0.77	1.00	0.76	0.99	0.72	0.94
180.0	0.73	0.94	0.69	0.90	0.76	0.99	0.75	0.97	0.72	0.93
182.0	0.72	0.94	0.69	0.90	0.76	0.98	0.75	0.97	0.71	0.92
184.0	0.72	0.93	0.68	0.89	0.76	0.98	0.74	0.96	0.71	0.92
186.0	0.72	0.93	0.68	0.89	0.75	0.97	0.74	0.96	0.70	0.91
188.0	0.71	0.92	0.68	0.88	0.75	0.97	0.73	0.95	0.70	0.91
190.0	0.71	0.92	0.67	0.88	0.74	0.96	0.73	0.95	0.69	0.90
192.0	0.70	0.91	0.67	0.88	0.74	0.96	0.72	0.94	0.69	0.90
194.0	0.70	0.91	0.66	0.87	0.73	0.95	0.72	0.94	0.69	0.89
196.0	0.69	0.90	0.66	0.87	0.73	0.95	0.72	0.93	0.68	0.89
198.0	0.69	0.90	0.65	0.86	0.72	0.94	0.71	0.93	0.68	0.88
200.0	0.69	0.89	0.65	0.86	0.72	0.94	0.71	0.92	0.67	0.88
202.0	0.68	0.89	0.65	0.85	0.72	0.93	0.70	0.92	0.67	0.87
204.0	0.68	0.89	0.64	0.85	0.71	0.93	0.70	0.91	0.67	0.87
206.0	0.67	0.88	0.64	0.84	0.71	0.92	0.69	0.91	0.66	0.86
208.0	0.67	0.88	0.63	0.84	0.70	0.92	0.69	0.90	0.66	0.86
210.0	0.66	0.87	0.63	0.83	0.70	0.91	0.69	0.90	0.65	0.85
212.0	0.66	0.87	0.63	0.83	0.69	0.91	0.68	0.89	0.65	0.85
214.0	0.66	0.86	0.62	0.83	0.69	0.90	0.68	0.89	0.64	0.84
216.0	0.65	0.86	0.62	0.82	0.69	0.90	0.67	0.88	0.64	0.84
218.0	0.65	0.85	0.61	0.82	0.68	0.89	0.67	0.88	0.64	0.83
220.0	0.64	0.85	0.61	0.81	0.68	0.89	0.66	0.87	0.63	0.83
222.0	0.64	0.85	0.61	0.81	0.67	0.89	0.66	0.87	0.63	0.83
224.0	0.64	0.84	0.60	0.80	0.67	0.88	0.66	0.87	0.62	0.82
226.0	0.63	0.84	0.60	0.80	0.67	0.88	0.65	0.86	0.62	0.82
228.0	0.63	0.83	0.59	0.80	0.66	0.87	0.65	0.86	0.62	0.81
230.0	0.62	0.83	0.59	0.79	0.66	0.87	0.64	0.85	0.61	0.81
232.0	0.62	0.82	0.59	0.79	0.65	0.86	0.64	0.85	0.61	0.80
234.0	0.62	0.82	0.58	0.78	0.65	0.86	0.64	0.84	0.61	0.80
236.0	0.61	0.81	0.58	0.78	0.65	0.85	0.63	0.84	0.60	0.80
238.0	0.61	0.81	0.58	0.77	0.64	0.85	0.63	0.83	0.60	0.79
240.0	0.61	0.81	0.57	0.77	0.64	0.85	0.62	0.83	0.59	0.79

Table C.2. RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
10.0	97.91	123.48	93.29	117.65	100.43	126.65	98.10	123.72	107.62	135.72
10.1	97.49	122.98	92.89	117.17	100.00	126.13	97.68	123.21	107.16	135.17
10.2	97.07	122.48	92.49	116.69	99.57	125.62	97.26	122.71	106.70	134.62
10.3	96.66	121.98	92.09	116.22	99.14	125.12	96.84	122.21	106.24	134.07
10.4	96.24	121.48	91.70	115.75	98.72	124.61	96.43	121.72	105.78	133.53
10.5	95.83	120.99	91.30	115.28	98.29	124.10	96.01	121.22	105.33	132.98
10.6	95.42	120.50	90.91	114.81	97.87	123.60	95.60	120.73	104.87	132.44
10.7	95.01	120.01	90.52	114.34	97.45	123.10	95.19	120.24	104.42	131.90
10.8	94.60	119.52	90.13	113.88	97.03	122.60	94.78	119.75	103.97	131.37
10.9	94.19	119.04	89.74	113.42	96.62	122.11	94.37	119.26	103.53	130.83
11.0	93.79	118.55	89.36	112.96	96.20	121.61	93.96	118.78	103.08	130.30
11.1	93.38	118.07	88.97	112.50	95.79	121.12	93.56	118.29	102.64	129.77
11.2	92.98	117.59	88.59	112.04	95.38	120.63	93.15	117.81	102.20	129.25
11.3	92.58	117.12	88.21	111.58	94.97	120.14	92.75	117.33	101.76	128.72
11.4	92.18	116.64	87.83	111.13	94.56	119.65	92.35	116.86	101.32	128.20
11.5	91.79	116.17	87.45	110.68	94.16	119.17	91.96	116.38	100.88	127.68
11.6	91.39	115.70	87.08	110.23	93.76	118.69	91.56	115.91	100.45	127.16
11.7	91.00	115.23	86.70	109.78	93.35	118.20	91.17	115.44	100.02	126.64
11.8	90.61	114.76	86.33	109.34	92.95	117.73	90.77	114.97	99.59	126.13
11.9	90.22	114.29	85.96	108.89	92.55	117.25	90.38	114.50	99.16	125.61
12.0	89.83	113.83	85.59	108.45	92.16	116.77	89.99	114.03	98.73	125.10
12.1	89.45	113.37	85.22	108.01	91.76	116.30	89.61	113.57	98.31	124.60
12.2	89.06	112.91	84.85	107.57	91.37	115.83	89.22	113.11	97.88	124.09
12.3	88.68	112.45	84.49	107.13	90.98	115.36	88.84	112.65	97.46	123.59
12.4	88.30	111.99	84.12	106.70	90.59	114.89	88.46	112.19	97.04	123.08
12.5	87.92	111.54	83.76	106.26	90.20	114.43	88.07	111.73	96.63	122.58
12.6	87.54	111.09	83.40	105.83	89.81	113.97	87.70	111.28	96.21	122.09
12.7	87.17	110.63	83.04	105.40	89.43	113.50	87.32	110.83	95.80	121.59
12.8	86.79	110.19	82.69	104.98	89.04	113.04	86.94	110.38	95.38	121.09
12.9	86.42	109.74	82.33	104.55	88.66	112.59	86.57	109.93	94.97	120.60
13.0	86.05	109.29	81.98	104.12	88.28	112.13	86.20	109.48	94.57	120.11
13.1	85.68	108.85	81.62	103.70	87.90	111.68	85.82	109.04	94.16	119.62
13.2	85.31	108.41	81.27	103.28	87.53	111.22	85.45	108.59	93.75	119.14
13.3	84.94	107.97	80.92	102.86	87.15	110.77	85.09	108.15	93.35	118.65
13.4	84.58	107.53	80.58	102.44	86.78	110.33	84.72	107.71	92.95	118.17
13.5	84.21	107.09	80.23	102.03	86.40	109.88	84.36	107.27	92.55	117.69
13.6	83.85	106.66	79.88	101.61	86.03	109.43	83.99	106.84	92.15	117.21
13.7	83.49	106.22	79.54	101.20	85.67	108.99	83.63	106.40	91.75	116.74
13.8	83.13	105.79	79.20	100.79	85.30	108.55	83.27	105.97	91.36	116.26
13.9	82.78	105.36	78.86	100.38	84.93	108.11	82.91	105.54	90.97	115.79

Table C.2 (continued). RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
14.0	82.42	104.94	78.52	99.97	84.57	107.67	82.56	105.11	90.58	115.32
14.1	82.07	104.51	78.18	99.56	84.21	107.24	82.20	104.68	90.19	114.85
14.2	81.71	104.09	77.85	99.16	83.84	106.80	81.85	104.26	89.80	114.39
14.3	81.36	103.66	77.51	98.76	83.48	106.37	81.49	103.83	89.41	113.92
14.4	81.01	103.24	77.18	98.36	83.13	105.94	81.14	103.41	89.03	113.46
14.5	80.66	102.82	76.85	97.96	82.77	105.51	80.79	102.99	88.64	113.00
14.6	80.32	102.41	76.52	97.56	82.42	105.08	80.45	102.57	88.26	112.54
14.7	79.97	101.99	76.19	97.16	82.06	104.66	80.10	102.15	87.88	112.08
14.8	79.63	101.58	75.86	96.77	81.71	104.23	79.76	101.74	87.51	111.62
14.9	79.29	101.16	75.53	96.37	81.36	103.81	79.41	101.32	87.13	111.17
15.0	78.95	100.75	75.21	95.98	81.01	103.39	79.07	100.91	86.75	110.72
15.1	78.75	100.52	75.02	95.76	80.81	103.15	78.88	100.68	86.54	110.46
15.2	78.56	100.29	74.84	95.54	80.61	102.91	78.68	100.45	86.33	110.21
15.3	78.37	100.06	74.66	95.32	80.42	102.67	78.49	100.21	86.12	109.95
15.4	78.18	99.83	74.48	95.10	80.22	102.43	78.30	99.98	85.91	109.70
15.5	77.99	99.60	74.29	94.88	80.02	102.20	78.11	99.75	85.70	109.45
15.6	77.80	99.37	74.11	94.66	79.83	101.96	77.92	99.52	85.49	109.19
15.7	77.61	99.14	73.93	94.44	79.63	101.72	77.73	99.29	85.28	108.94
15.8	77.42	98.91	73.75	94.22	79.44	101.49	77.54	99.06	85.08	108.69
15.9	77.23	98.68	73.57	94.00	79.24	101.25	77.35	98.83	84.87	108.44
16.0	77.05	98.46	73.39	93.79	79.05	101.02	77.16	98.61	84.66	108.19
16.1	76.86	98.23	73.21	93.57	78.85	100.78	76.97	98.38	84.46	107.94
16.2	76.67	98.00	73.03	93.35	78.66	100.55	76.79	98.15	84.25	107.69
16.3	76.48	97.78	72.85	93.14	78.47	100.31	76.60	97.92	84.04	107.44
16.4	76.30	97.55	72.68	92.92	78.28	100.08	76.41	97.70	83.84	107.19
16.5	76.11	97.33	72.50	92.71	78.08	99.85	76.23	97.47	83.64	106.95
16.6	75.93	97.10	72.32	92.49	77.89	99.62	76.04	97.25	83.43	106.70
16.7	75.74	96.88	72.14	92.28	77.70	99.39	75.85	97.02	83.23	106.45
16.8	75.56	96.66	71.97	92.06	77.51	99.16	75.67	96.80	83.02	106.21
16.9	75.37	96.43	71.79	91.85	77.32	98.93	75.48	96.57	82.82	105.96
17.0	75.19	96.21	71.62	91.64	77.13	98.70	75.30	96.35	82.62	105.72
17.1	75.01	95.99	71.44	91.43	76.94	98.47	75.12	96.13	82.42	105.47
17.2	74.83	95.77	71.27	91.21	76.76	98.24	74.93	95.91	82.22	105.23
17.3	74.64	95.55	71.09	91.00	76.57	98.01	74.75	95.69	82.02	104.99
17.4	74.46	95.33	70.92	90.79	76.38	97.78	74.57	95.46	81.82	104.75
17.5	74.28	95.11	70.75	90.58	76.19	97.56	74.39	95.24	81.62	104.50
17.6	74.10	94.89	70.57	90.37	76.01	97.33	74.20	95.02	81.42	104.26
17.7	73.92	94.67	70.40	90.16	75.82	97.10	74.02	94.80	81.22	104.02
17.8	73.74	94.45	70.23	89.96	75.63	96.88	73.84	94.59	81.02	103.78
17.9	73.56	94.23	70.06	89.75	75.45	96.65	73.66	94.37	80.83	103.54

Table C.2 (continued). RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
18.0	73.38	94.02	69.89	89.54	75.26	96.43	73.48	94.15	80.63	103.30
18.1	73.20	93.80	69.72	89.33	75.08	96.21	73.30	93.93	80.43	103.07
18.2	73.02	93.59	69.54	89.13	74.90	95.98	73.13	93.72	80.24	102.83
18.3	72.85	93.37	69.37	88.92	74.71	95.76	72.95	93.50	80.04	102.59
18.4	72.67	93.15	69.21	88.71	74.53	95.54	72.77	93.28	79.84	102.35
18.5	72.49	92.94	69.04	88.51	74.35	95.32	72.59	93.07	79.65	102.12
18.6	72.32	92.73	68.87	88.30	74.16	95.10	72.41	92.85	79.46	101.88
18.7	72.14	92.51	68.70	88.10	73.98	94.88	72.24	92.64	79.26	101.65
18.8	71.96	92.30	68.53	87.90	73.80	94.66	72.06	92.42	79.07	101.41
18.9	71.79	92.09	68.36	87.69	73.62	94.44	71.89	92.21	78.88	101.18
19.0	71.61	91.87	68.20	87.49	73.44	94.22	71.71	92.00	78.68	100.94
19.1	71.44	91.66	68.03	87.29	73.26	94.00	71.54	91.79	78.49	100.71
19.2	71.27	91.45	67.86	87.09	73.08	93.78	71.36	91.57	78.30	100.48
19.3	71.09	91.24	67.70	86.88	72.90	93.56	71.19	91.36	78.11	100.25
19.4	70.92	91.03	67.53	86.68	72.72	93.35	71.01	91.15	77.92	100.02
19.5	70.75	90.82	67.37	86.48	72.54	93.13	70.84	90.94	77.73	99.78
19.6	70.57	90.61	67.20	86.28	72.37	92.91	70.67	90.73	77.54	99.55
19.7	70.40	90.40	67.04	86.08	72.19	92.70	70.49	90.52	77.35	99.32
19.8	70.23	90.19	66.88	85.88	72.01	92.48	70.32	90.31	77.16	99.10
19.9	70.06	89.99	66.71	85.69	71.84	92.27	70.15	90.10	76.97	98.87
20.0	69.89	89.78	66.55	85.49	71.66	92.05	69.98	89.89	76.79	98.64
20.1	69.72	89.57	66.39	85.29	71.49	91.84	69.81	89.69	76.60	98.41
20.2	69.55	89.37	66.22	85.09	71.31	91.63	69.64	89.48	76.41	98.18
20.3	69.38	89.16	66.06	84.90	71.14	91.41	69.47	89.27	76.23	97.96
20.4	69.21	88.96	65.90	84.70	70.96	91.20	69.30	89.07	76.04	97.73
20.5	69.04	88.75	65.74	84.50	70.79	90.99	69.13	88.86	75.85	97.51
20.6	68.88	88.55	65.58	84.31	70.61	90.78	68.96	88.66	75.67	97.28
20.7	68.71	88.34	65.42	84.11	70.44	90.57	68.79	88.45	75.49	97.06
20.8	68.54	88.14	65.26	83.92	70.27	90.36	68.63	88.25	75.30	96.83
20.9	68.37	87.94	65.10	83.72	70.10	90.15	68.46	88.04	75.12	96.61
21.0	68.21	87.73	64.94	83.53	69.92	89.94	68.29	87.84	74.93	96.38
21.1	68.04	87.53	64.78	83.34	69.75	89.73	68.12	87.64	74.75	96.16
21.2	67.88	87.33	64.62	83.14	69.58	89.52	67.96	87.43	74.57	95.94
21.3	67.71	87.13	64.47	82.95	69.41	89.32	67.79	87.23	74.39	95.72
21.4	67.55	86.93	64.31	82.76	69.24	89.11	67.63	87.03	74.21	95.50
21.5	67.38	86.73	64.15	82.57	69.07	88.90	67.46	86.83	74.03	95.28
21.6	67.22	86.53	63.99	82.38	68.90	88.70	67.30	86.63	73.85	95.06
21.7	67.05	86.33	63.84	82.19	68.73	88.49	67.13	86.43	73.66	94.84
21.8	66.89	86.13	63.68	82.00	68.57	88.28	66.97	86.23	73.49	94.62
21.9	66.73	85.93	63.53	81.81	68.40	88.08	66.81	86.03	73.31	94.40

Table C.2 (continued). RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
22.0	66.57	85.73	63.37	81.62	68.23	87.88	66.64	85.83	73.13	94.18
22.1	66.40	85.53	63.22	81.43	68.06	87.67	66.48	85.63	72.95	93.97
22.2	66.24	85.34	63.06	81.24	67.90	87.47	66.32	85.44	72.77	93.75
22.3	66.08	85.14	62.91	81.05	67.73	87.27	66.16	85.24	72.59	93.53
22.4	65.92	84.94	62.75	80.87	67.56	87.06	66.00	85.04	72.42	93.32
22.5	65.76	84.75	62.60	80.68	67.40	86.86	65.83	84.85	72.24	93.10
22.6	65.60	84.55	62.45	80.49	67.23	86.66	65.67	84.65	72.06	92.89
22.7	65.44	84.36	62.30	80.31	67.07	86.46	65.51	84.45	71.89	92.67
22.8	65.28	84.16	62.14	80.12	66.90	86.26	65.35	84.26	71.71	92.46
22.9	65.12	83.97	61.99	79.93	66.74	86.06	65.19	84.06	71.54	92.24
23.0	64.96	83.78	61.84	79.75	66.58	85.86	65.04	83.87	71.36	92.03
23.1	64.81	83.58	61.69	79.57	66.41	85.66	64.88	83.68	71.19	91.82
23.2	64.65	83.39	61.54	79.38	66.25	85.46	64.72	83.48	71.02	91.61
23.3	64.49	83.20	61.39	79.20	66.09	85.26	64.56	83.29	70.84	91.40
23.4	64.33	83.01	61.24	79.01	65.93	85.06	64.40	83.10	70.67	91.19
23.5	64.18	82.82	61.09	78.83	65.77	84.87	64.25	82.91	70.50	90.97
23.6	64.02	82.63	60.94	78.65	65.60	84.67	64.09	82.71	70.33	90.76
23.7	63.86	82.44	60.79	78.47	65.44	84.47	63.93	82.52	70.15	90.56
23.8	63.71	82.25	60.64	78.29	65.28	84.28	63.78	82.33	69.98	90.35
23.9	63.55	82.06	60.49	78.10	65.12	84.08	63.62	82.14	69.81	90.14
24.0	63.40	81.87	60.35	77.92	64.96	83.89	63.47	81.95	69.64	89.93
24.1	63.25	81.68	60.20	77.74	64.80	83.69	63.31	81.76	69.47	89.72
24.2	63.09	81.49	60.05	77.56	64.65	83.50	63.16	81.58	69.30	89.51
24.3	62.94	81.30	59.90	77.38	64.49	83.30	63.00	81.39	69.13	89.31
24.4	62.78	81.12	59.76	77.21	64.33	83.11	62.85	81.20	68.97	89.10
24.5	62.63	80.93	59.61	77.03	64.17	82.92	62.70	81.01	68.80	88.90
24.6	62.48	80.74	59.47	76.85	64.01	82.73	62.54	80.82	68.63	88.69
24.7	62.33	80.56	59.32	76.67	63.86	82.53	62.39	80.64	68.46	88.49
24.8	62.18	80.37	59.18	76.49	63.70	82.34	62.24	80.45	68.30	88.28
24.9	62.02	80.19	59.03	76.32	63.55	82.15	62.09	80.27	68.13	88.08
25.0	61.87	80.00	58.89	76.14	63.39	81.96	61.93	80.08	67.96	87.88
25.1	61.72	79.82	58.74	75.96	63.23	81.77	61.78	79.90	67.80	87.67
25.2	61.57	79.63	58.60	75.79	63.08	81.58	61.63	79.71	67.63	87.47
25.3	61.42	79.45	58.46	75.61	62.92	81.39	61.48	79.53	67.47	87.27
25.4	61.27	79.27	58.31	75.44	62.77	81.20	61.33	79.34	67.30	87.07
25.5	61.12	79.08	58.17	75.26	62.62	81.01	61.18	79.16	67.14	86.87
25.6	60.98	78.90	58.03	75.09	62.46	80.83	61.03	78.98	66.98	86.67
25.7	60.83	78.72	57.89	74.92	62.31	80.64	60.88	78.79	66.81	86.47
25.8	60.68	78.54	57.75	74.74	62.16	80.45	60.74	78.61	66.65	86.27
25.9	60.53	78.36	57.61	74.57	62.01	80.27	60.59	78.43	66.49	86.07

Table C.2 (continued). RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
26.0	60.38	78.18	57.46	74.40	61.85	80.08	60.44	78.25	66.32	85.87
26.1	60.24	78.00	57.32	74.23	61.70	79.89	60.29	78.07	66.16	85.67
26.2	60.09	77.82	57.18	74.05	61.55	79.71	60.15	77.89	66.00	85.47
26.3	59.94	77.64	57.04	73.88	61.40	79.52	60.00	77.71	65.84	85.27
26.4	59.80	77.46	56.91	73.71	61.25	79.34	59.85	77.53	65.68	85.08
26.5	59.65	77.28	56.77	73.54	61.10	79.16	59.71	77.35	65.52	84.88
26.6	59.51	77.10	56.63	73.37	60.95	78.97	59.56	77.17	65.36	84.69
26.7	59.36	76.92	56.49	73.20	60.80	78.79	59.42	76.99	65.20	84.49
26.8	59.22	76.75	56.35	73.03	60.65	78.61	59.27	76.82	65.04	84.30
26.9	59.07	76.57	56.21	72.86	60.50	78.42	59.13	76.64	64.88	84.10
27.0	58.93	76.39	56.08	72.69	60.35	78.24	58.98	76.46	64.73	83.91
27.1	58.79	76.22	55.94	72.53	60.21	78.06	58.84	76.28	64.57	83.71
27.2	58.64	76.04	55.80	72.36	60.06	77.88	58.69	76.11	64.41	83.52
27.3	58.50	75.87	55.67	72.19	59.91	77.70	58.55	75.93	64.25	83.33
27.4	58.36	75.69	55.53	72.02	59.77	77.52	58.41	75.76	64.10	83.13
27.5	58.22	75.52	55.39	71.86	59.62	77.34	58.27	75.58	63.94	82.94
27.6	58.08	75.34	55.26	71.69	59.47	77.16	58.12	75.41	63.78	82.75
27.7	57.93	75.17	55.12	71.53	59.33	76.98	57.98	75.23	63.63	82.56
27.8	57.79	75.00	54.99	71.36	59.18	76.80	57.84	75.06	63.47	82.37
27.9	57.65	74.83	54.85	71.19	59.04	76.62	57.70	74.89	63.32	82.18
28.0	57.51	74.65	54.72	71.03	58.89	76.44	57.56	74.71	63.16	81.99
28.1	57.37	74.48	54.59	70.87	58.75	76.27	57.42	74.54	63.01	81.80
28.2	57.23	74.31	54.45	70.70	58.60	76.09	57.28	74.37	62.86	81.61
28.3	57.09	74.14	54.32	70.54	58.46	75.91	57.14	74.20	62.70	81.42
28.4	56.95	73.97	54.19	70.38	58.32	75.74	57.00	74.03	62.55	81.24
28.5	56.82	73.80	54.06	70.21	58.17	75.56	56.86	73.85	62.40	81.05
28.6	56.68	73.63	53.92	70.05	58.03	75.39	56.72	73.68	62.25	80.86
28.7	56.54	73.46	53.79	69.89	57.89	75.21	56.58	73.51	62.09	80.67
28.8	56.40	73.29	53.66	69.73	57.75	75.04	56.44	73.34	61.94	80.49
28.9	56.26	73.12	53.53	69.56	57.61	74.86	56.31	73.17	61.79	80.30
29.0	56.13	72.95	53.40	69.40	57.47	74.69	56.17	73.01	61.64	80.12
29.1	55.99	72.78	53.27	69.24	57.32	74.52	56.03	72.84	61.49	79.93
29.2	55.85	72.61	53.14	69.08	57.18	74.34	55.90	72.67	61.34	79.75
29.3	55.72	72.45	53.01	68.92	57.04	74.17	55.76	72.50	61.19	79.56
29.4	55.58	72.28	52.88	68.76	56.90	74.00	55.62	72.33	61.04	79.38
29.5	55.45	72.11	52.75	68.60	56.77	73.83	55.49	72.17	60.89	79.20
29.6	55.31	71.95	52.62	68.45	56.63	73.66	55.35	72.00	60.74	79.01
29.7	55.18	71.78	52.49	68.29	56.49	73.49	55.22	71.83	60.60	78.83
29.8	55.04	71.62	52.36	68.13	56.35	73.31	55.08	71.67	60.45	78.65
29.9	54.91	71.45	52.24	67.97	56.21	73.14	54.95	71.50	60.30	78.47

Table C.2 (continued). RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 0.2 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
30.0	54.78	71.29	52.11	67.82	56.07	72.98	54.81	71.34	60.15	78.29
30.2	54.65	71.14	51.99	67.69	55.94	72.83	54.69	71.20	60.01	78.14
30.4	54.53	71.00	51.87	67.56	55.81	72.69	54.56	71.06	59.88	77.99
30.6	54.40	70.85	51.75	67.44	55.68	72.54	54.43	70.92	59.74	77.84
30.8	54.28	70.71	51.63	67.31	55.54	72.40	54.31	70.78	59.60	77.69
31.0	54.15	70.57	51.51	67.19	55.41	72.25	54.18	70.64	59.46	77.54
31.2	54.03	70.42	51.40	67.06	55.28	72.11	54.05	70.50	59.32	77.39
31.4	53.91	70.28	51.28	66.94	55.15	71.97	53.93	70.36	59.18	77.24
31.6	53.78	70.14	51.16	66.81	55.02	71.83	53.80	70.22	59.05	77.09
31.8	53.66	69.99	51.04	66.69	54.89	71.68	53.68	70.08	58.91	76.94
32.0	53.54	69.85	50.93	66.57	54.76	71.54	53.55	69.94	58.77	76.79
32.2	53.42	69.71	50.81	66.44	54.63	71.40	53.43	69.80	58.64	76.65
32.4	53.29	69.57	50.69	66.32	54.50	71.26	53.30	69.67	58.50	76.50
32.6	53.17	69.43	50.58	66.20	54.37	71.12	53.18	69.53	58.36	76.35
32.8	53.05	69.29	50.46	66.07	54.24	70.98	53.05	69.39	58.23	76.20
33.0	52.93	69.15	50.34	65.95	54.11	70.84	52.93	69.26	58.09	76.06
33.2	52.81	69.01	50.23	65.83	53.99	70.70	52.81	69.12	57.96	75.91
33.4	52.69	68.87	50.11	65.71	53.86	70.55	52.69	68.98	57.82	75.77
33.6	52.57	68.73	50.00	65.58	53.73	70.42	52.56	68.85	57.69	75.62
33.8	52.45	68.59	49.88	65.46	53.60	70.28	52.44	68.71	57.55	75.47
34.0	52.33	68.45	49.77	65.34	53.48	70.14	52.32	68.57	57.42	75.33
34.2	52.21	68.31	49.66	65.22	53.35	70.00	52.20	68.44	57.29	75.18
34.4	52.09	68.17	49.54	65.10	53.22	69.86	52.07	68.30	57.15	75.04
34.6	51.97	68.03	49.43	64.98	53.10	69.72	51.95	68.17	57.02	74.90
34.8	51.85	67.89	49.32	64.86	52.97	69.58	51.83	68.04	56.89	74.75
35.0	51.73	67.75	49.20	64.74	52.85	69.44	51.71	67.90	56.76	74.61
35.2	51.61	67.62	49.09	64.62	52.72	69.31	51.59	67.77	56.63	74.46
35.4	51.50	67.48	48.98	64.50	52.60	69.17	51.47	67.63	56.49	74.32
35.6	51.38	67.34	48.86	64.38	52.47	69.03	51.35	67.50	56.36	74.18
35.8	51.26	67.21	48.75	64.26	52.35	68.90	51.23	67.37	56.23	74.04
36.0	51.14	67.07	48.64	64.14	52.23	68.76	51.11	67.23	56.10	73.89
36.2	51.03	66.93	48.53	64.02	52.10	68.62	50.99	67.10	55.97	73.75
36.4	50.91	66.80	48.42	63.90	51.98	68.49	50.88	66.97	55.84	73.61
36.6	50.79	66.66	48.31	63.78	51.86	68.35	50.76	66.84	55.71	73.47
36.8	50.68	66.53	48.20	63.66	51.73	68.22	50.64	66.71	55.58	73.33
37.0	50.56	66.39	48.09	63.54	51.61	68.08	50.52	66.57	55.45	73.18
37.2	50.45	66.26	47.98	63.43	51.49	67.94	50.40	66.44	55.32	73.04
37.4	50.33	66.12	47.87	63.31	51.37	67.81	50.29	66.31	55.20	72.90
37.6	50.22	65.99	47.76	63.19	51.24	67.68	50.17	66.18	55.07	72.76
37.8	50.10	65.85	47.65	63.07	51.12	67.54	50.05	66.05	54.94	72.62

Table C.2 (continued). RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 0.5 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
38.0	49.99	65.72	47.54	62.96	51.00	67.41	49.94	65.92	54.81	72.48
38.5	49.70	65.39	47.26	62.66	50.70	67.07	49.65	65.60	54.49	72.14
39.0	49.42	65.06	46.99	62.37	50.40	66.74	49.36	65.27	54.18	71.79
39.5	49.14	64.73	46.73	62.09	50.10	66.41	49.07	64.95	53.86	71.44
40.0	48.86	64.40	46.46	61.80	49.81	66.08	48.78	64.63	53.55	71.10
40.5	48.58	64.07	46.19	61.51	49.51	65.76	48.50	64.31	53.24	70.76
41.0	48.30	63.75	45.93	61.23	49.22	65.43	48.22	64.00	52.93	70.42
41.5	48.03	63.42	45.67	60.94	48.93	65.11	47.94	63.68	52.63	70.08
42.0	47.75	63.10	45.40	60.66	48.64	64.79	47.66	63.37	52.32	69.75
42.5	47.48	62.78	45.14	60.38	48.35	64.47	47.38	63.06	52.02	69.41
43.0	47.21	62.46	44.89	60.10	48.07	64.15	47.11	62.74	51.72	69.08
43.5	46.94	62.15	44.63	59.82	47.78	63.83	46.84	62.44	51.42	68.75
44.0	46.67	61.83	44.37	59.54	47.50	63.51	46.56	62.13	51.12	68.42
44.5	46.41	61.52	44.12	59.27	47.22	63.20	46.29	61.82	50.82	68.09
45.0	46.14	61.21	43.87	58.99	46.94	62.89	46.02	61.52	50.53	67.76
45.5	45.88	60.90	43.62	58.72	46.67	62.57	45.76	61.21	50.23	67.43
46.0	45.62	60.59	43.37	58.45	46.39	62.27	45.49	60.91	49.94	67.11
46.5	45.36	60.28	43.12	58.18	46.12	61.96	45.23	60.61	49.65	66.79
47.0	45.10	59.97	42.87	57.91	45.84	61.65	44.96	60.32	49.37	66.47
47.5	44.84	59.67	42.63	57.64	45.57	61.35	44.70	60.02	49.08	66.15
48.0	44.59	59.37	42.38	57.37	45.30	61.04	44.44	59.72	48.80	65.83
48.5	44.33	59.07	42.14	57.10	45.04	60.74	44.18	59.43	48.51	65.52
49.0	44.08	58.77	41.90	56.84	44.77	60.44	43.93	59.14	48.23	65.20
49.5	43.83	58.47	41.66	56.58	44.50	60.14	43.67	58.84	47.95	64.89
50.0	43.58	58.17	41.42	56.31	44.24	59.84	43.42	58.55	47.67	64.58
50.5	43.33	57.88	41.18	56.05	43.98	59.55	43.17	58.27	47.40	64.27
51.0	43.08	57.58	40.95	55.79	43.72	59.25	42.92	57.98	47.12	63.96
51.5	42.84	57.29	40.71	55.53	43.46	58.96	42.67	57.69	46.85	63.65
52.0	42.59	57.00	40.48	55.28	43.21	58.67	42.42	57.41	46.58	63.34
52.5	42.35	56.71	40.25	55.02	42.95	58.38	42.17	57.13	46.31	63.04
53.0	42.11	56.43	40.02	54.77	42.70	58.09	41.93	56.85	46.04	62.74
53.5	41.87	56.14	39.79	54.51	42.44	57.80	41.68	56.57	45.77	62.44
54.0	41.63	55.86	39.56	54.26	42.19	57.52	41.44	56.29	45.51	62.14
54.5	41.39	55.57	39.34	54.01	41.94	57.23	41.20	56.01	45.24	61.84
55.0	41.15	55.29	39.11	53.76	41.70	56.95	40.96	55.73	44.98	61.54
55.5	40.92	55.01	38.89	53.51	41.45	56.67	40.72	55.46	44.72	61.25
56.0	40.69	54.73	38.66	53.26	41.21	56.39	40.49	55.19	44.46	60.95
56.5	40.46	54.45	38.44	53.01	40.96	56.11	40.25	54.92	44.20	60.66
57.0	40.22	54.18	38.22	52.77	40.72	55.83	40.02	54.64	43.95	60.37
57.5	39.99	53.90	38.00	52.52	40.48	55.55	39.78	54.38	43.69	60.08

Table C.2 (continued). RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 1.0 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
58.0	39.77	53.63	37.79	52.28	40.24	55.28	39.55	54.11	43.44	59.79
59.0	39.31	53.09	37.36	51.80	39.77	54.73	39.10	53.58	42.94	59.22
60.0	38.87	52.55	36.93	51.32	39.30	54.19	38.64	53.05	42.44	58.65
61.0	38.52	52.11	36.62	50.90	38.97	53.76	38.30	52.61	42.08	58.17
62.0	38.18	51.67	36.31	50.48	38.64	53.32	37.97	52.17	41.73	57.69
63.0	37.85	51.24	36.00	50.07	38.32	52.89	37.64	51.73	41.38	57.21
64.0	37.51	50.81	35.70	49.67	38.00	52.47	37.31	51.30	41.03	56.74
65.0	37.18	50.38	35.40	49.26	37.68	52.05	36.98	50.87	40.68	56.27
66.0	36.85	49.96	35.10	48.86	37.37	51.63	36.66	50.45	40.34	55.81
67.0	36.53	49.54	34.80	48.46	37.05	51.21	36.34	50.03	40.00	55.35
68.0	36.21	49.12	34.51	48.07	36.74	50.80	36.02	49.61	39.66	54.89
69.0	35.89	48.71	34.22	47.68	36.44	50.39	35.70	49.20	39.33	54.44
70.0	35.57	48.30	33.93	47.29	36.13	49.98	35.39	48.79	38.99	53.99
71.0	35.26	47.90	33.64	46.90	35.83	49.58	35.08	48.38	38.67	53.54
72.0	34.95	47.50	33.36	46.52	35.53	49.18	34.77	47.97	38.34	53.10
73.0	34.64	47.10	33.08	46.14	35.23	48.79	34.47	47.57	38.02	52.67
74.0	34.33	46.70	32.80	45.77	34.94	48.39	34.17	47.18	37.70	52.23
75.0	34.03	46.31	32.52	45.39	34.64	48.00	33.87	46.78	37.38	51.80
76.0	33.73	45.92	32.25	45.02	34.35	47.62	33.57	46.39	37.06	51.37
77.0	33.43	45.54	31.98	44.66	34.07	47.24	33.28	46.01	36.75	50.95
78.0	33.14	45.15	31.71	44.29	33.78	46.85	32.98	45.62	36.44	50.53
79.0	32.84	44.77	31.44	43.93	33.50	46.48	32.70	45.24	36.13	50.11
80.0	32.55	44.40	31.17	43.58	33.22	46.10	32.41	44.86	35.83	49.70
81.0	32.27	44.03	30.91	43.22	32.94	45.73	32.13	44.49	35.53	49.29
82.0	31.98	43.66	30.65	42.87	32.66	45.36	31.84	44.12	35.23	48.88
83.0	31.70	43.29	30.39	42.52	32.39	45.00	31.57	43.75	34.93	48.48
84.0	31.42	42.93	30.13	42.17	32.12	44.64	31.29	43.39	34.63	48.08
85.0	31.14	42.57	29.88	41.83	31.85	44.28	31.01	43.02	34.34	47.69
86.0	30.87	42.21	29.63	41.49	31.58	43.92	30.74	42.66	34.05	47.29
87.0	30.60	41.86	29.38	41.15	31.32	43.57	30.47	42.31	33.77	46.90
88.0	30.33	41.50	29.13	40.82	31.06	43.22	30.21	41.95	33.48	46.52
89.0	30.06	41.16	28.88	40.49	30.80	42.87	29.94	41.60	33.20	46.13
90.0	29.79	40.81	28.64	40.16	30.54	42.52	29.68	41.26	32.92	45.75
91.0	29.53	40.47	28.40	39.83	30.29	42.18	29.42	40.91	32.64	45.37
92.0	29.27	40.13	28.16	39.50	30.03	41.84	29.16	40.57	32.37	45.00
93.0	29.01	39.79	27.92	39.18	29.78	41.51	28.91	40.23	32.09	44.63
94.0	28.75	39.46	27.69	38.86	29.53	41.17	28.65	39.90	31.82	44.26
95.0	28.50	39.13	27.45	38.55	29.28	40.84	28.40	39.56	31.55	43.90
96.0	28.25	38.80	27.22	38.23	29.04	40.51	28.15	39.23	31.29	43.53
97.0	28.00	38.47	26.99	37.92	28.80	40.19	27.91	38.91	31.02	43.18
98.0	27.75	38.15	26.76	37.61	28.56	39.86	27.66	38.58	30.76	42.82

Table C.2 (continued). RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 2.0 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
100.0	27.27	37.51	26.31	37.00	28.08	39.22	27.18	37.94	30.25	42.12
102.0	26.79	36.89	25.87	36.40	27.61	38.59	26.71	37.31	29.74	41.43
104.0	26.32	36.27	25.44	35.81	27.15	37.98	26.24	36.69	29.24	40.75
106.0	25.85	35.66	25.01	35.23	26.70	37.37	25.78	36.08	28.75	40.08
108.0	25.40	35.07	24.59	34.66	26.25	36.77	25.33	35.48	28.26	39.42
110.0	24.95	34.48	24.18	34.10	25.82	36.18	24.89	34.89	27.79	38.77
112.0	24.51	33.90	23.77	33.55	25.39	35.60	24.46	34.31	27.32	38.13
114.0	24.08	33.34	23.37	33.00	24.96	35.03	24.03	33.74	26.86	37.51
116.0	23.66	32.78	22.98	32.47	24.55	34.47	23.61	33.18	26.41	36.89
118.0	23.24	32.23	22.59	31.94	24.14	33.91	23.20	32.63	25.97	36.29
120.0	22.84	31.69	22.21	31.42	23.73	33.37	22.80	32.09	25.53	35.69
122.0	22.60	31.29	21.99	31.01	23.49	32.94	22.57	31.67	25.27	35.23
124.0	22.37	30.90	21.77	30.61	23.25	32.51	22.34	31.26	25.01	34.77
126.0	22.14	30.51	21.55	30.21	23.01	32.09	22.11	30.86	24.76	34.33
128.0	21.92	30.12	21.33	29.82	22.78	31.68	21.88	30.46	24.50	33.88
130.0	21.69	29.74	21.11	29.43	22.54	31.27	21.66	30.06	24.25	33.45
132.0	21.47	29.36	20.90	29.05	22.31	30.86	21.44	29.68	24.00	33.01
134.0	21.25	28.99	20.69	28.67	22.08	30.47	21.22	29.29	23.76	32.59
136.0	21.04	28.63	20.48	28.30	21.85	30.07	21.01	28.91	23.52	32.17
138.0	20.82	28.26	20.27	27.93	21.63	29.68	20.79	28.54	23.27	31.75
140.0	20.61	27.91	20.07	27.57	21.41	29.30	20.58	28.17	23.04	31.34
142.0	20.40	27.55	19.86	27.21	21.19	28.92	20.37	27.81	22.80	30.94
144.0	20.19	27.20	19.66	26.86	20.97	28.55	20.16	27.45	22.57	30.54
146.0	19.98	26.86	19.46	26.51	20.76	28.18	19.96	27.09	22.34	30.14
148.0	19.78	26.52	19.27	26.16	20.54	27.81	19.76	26.74	22.11	29.75
150.0	19.58	26.19	19.07	25.82	20.33	27.46	19.56	26.39	21.88	29.37
152.0	19.38	25.85	18.88	25.49	20.12	27.10	19.36	26.05	21.66	28.99
154.0	19.18	25.53	18.69	25.15	19.92	26.75	19.16	25.72	21.44	28.62
156.0	18.98	25.20	18.50	24.83	19.71	26.41	18.96	25.38	21.22	28.25
158.0	18.79	24.89	18.31	24.51	19.51	26.06	18.77	25.06	21.00	27.88
160.0	18.60	24.57	18.13	24.19	19.31	25.73	18.58	24.73	20.79	27.52
162.0	18.41	24.26	17.95	23.87	19.11	25.39	18.39	24.41	20.57	27.17
164.0	18.22	23.95	17.76	23.56	18.92	25.07	18.20	24.10	20.36	26.82
166.0	18.03	23.65	17.58	23.26	18.72	24.74	18.02	23.78	20.15	26.47
168.0	17.85	23.35	17.41	22.95	18.53	24.42	17.84	23.48	19.95	26.13

Table C.2 (continued). RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 2.0 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
170.0	17.67	23.06	17.23	22.65	18.34	24.11	17.65	23.17	19.74	25.79
172.0	17.49	22.76	17.06	22.36	18.15	23.80	17.47	22.87	19.54	25.46
174.0	17.31	22.48	16.88	22.07	17.96	23.49	17.30	22.58	19.34	25.13
176.0	17.13	22.19	16.71	21.78	17.78	23.19	17.12	22.29	19.14	24.80
178.0	16.96	21.91	16.55	21.50	17.60	22.89	16.95	22.00	18.95	24.48
180.0	16.78	21.63	16.38	21.22	17.42	22.59	16.77	21.71	18.75	24.17
182.0	16.68	21.52	16.28	21.11	17.31	22.48	16.67	21.60	18.64	24.05
184.0	16.58	21.41	16.18	21.00	17.21	22.36	16.57	21.49	18.53	23.93
186.0	16.48	21.30	16.08	20.90	17.10	22.25	16.47	21.38	18.42	23.81
188.0	16.38	21.19	15.99	20.79	17.00	22.14	16.37	21.27	18.31	23.69
190.0	16.28	21.08	15.89	20.68	16.89	22.02	16.27	21.16	18.20	23.57
192.0	16.19	20.97	15.79	20.58	16.79	21.91	16.17	21.05	18.10	23.45
194.0	16.09	20.86	15.70	20.47	16.69	21.80	16.07	20.94	17.99	23.33
196.0	15.99	20.75	15.60	20.37	16.59	21.69	15.97	20.84	17.88	23.21
198.0	15.90	20.65	15.51	20.27	16.48	21.58	15.87	20.73	17.78	23.10
200.0	15.80	20.54	15.41	20.16	16.38	21.47	15.78	20.62	17.67	22.98
202.0	15.70	20.43	15.32	20.06	16.28	21.36	15.68	20.52	17.57	22.86
204.0	15.61	20.33	15.23	19.96	16.18	21.26	15.58	20.41	17.46	22.75
206.0	15.52	20.22	15.13	19.86	16.09	21.15	15.49	20.31	17.36	22.64
208.0	15.42	20.12	15.04	19.76	15.99	21.04	15.39	20.20	17.26	22.52
210.0	15.33	20.01	14.95	19.65	15.89	20.93	15.30	20.10	17.15	22.41
212.0	15.24	19.91	14.86	19.55	15.79	20.83	15.21	20.00	17.05	22.30
214.0	15.15	19.81	14.77	19.45	15.70	20.72	15.11	19.89	16.95	22.18
216.0	15.05	19.70	14.68	19.36	15.60	20.62	15.02	19.79	16.85	22.07
218.0	14.96	19.60	14.59	19.26	15.51	20.51	14.93	19.69	16.75	21.96
220.0	14.87	19.50	14.51	19.16	15.41	20.41	14.84	19.59	16.65	21.85
222.0	14.78	19.40	14.42	19.06	15.32	20.31	14.75	19.49	16.55	21.74
224.0	14.70	19.30	14.33	18.96	15.22	20.20	14.66	19.39	16.45	21.63
226.0	14.61	19.20	14.24	18.87	15.13	20.10	14.57	19.29	16.36	21.52
228.0	14.52	19.10	14.16	18.77	15.04	20.00	14.48	19.19	16.26	21.41
230.0	14.43	19.00	14.07	18.68	14.95	19.90	14.39	19.09	16.16	21.31
232.0	14.34	18.90	13.99	18.58	14.86	19.80	14.30	18.99	16.07	21.20
234.0	14.26	18.81	13.90	18.49	14.77	19.70	14.21	18.90	15.97	21.09
236.0	14.17	18.71	13.82	18.39	14.68	19.60	14.13	18.80	15.88	20.99
238.0	14.09	18.61	13.73	18.30	14.59	19.50	14.04	18.70	15.78	20.88
240.0	14.00	18.51	13.65	18.20	14.50	19.40	13.96	18.61	15.69	20.78

Table C.2 (continued). RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
10.0	108.20	136.45	103.86	130.97	112.39	141.73	111.64	140.79	106.40	134.18
10.1	107.73	135.89	103.41	130.44	111.91	141.16	111.16	140.22	105.95	133.64
10.2	107.27	135.34	102.97	129.92	111.43	140.58	110.68	139.65	105.49	133.10
10.3	106.81	134.80	102.53	129.39	110.95	140.01	110.21	139.08	105.04	132.55
10.4	106.35	134.25	102.09	128.87	110.47	139.45	109.74	138.52	104.59	132.02
10.5	105.90	133.70	101.65	128.35	110.00	138.88	109.26	137.95	104.14	131.48
10.6	105.44	133.16	101.22	127.83	109.52	138.32	108.79	137.39	103.69	130.94
10.7	104.99	132.62	100.79	127.31	109.05	137.76	108.33	136.84	103.24	130.41
10.8	104.54	132.09	100.36	126.80	108.58	137.20	107.86	136.28	102.80	129.88
10.9	104.09	131.55	99.93	126.29	108.12	136.64	107.40	135.73	102.35	129.35
11.0	103.65	131.02	99.50	125.78	107.65	136.08	106.93	135.17	101.91	128.83
11.1	103.20	130.49	99.07	125.27	107.19	135.53	106.47	134.63	101.48	128.31
11.2	102.76	129.96	98.65	124.76	106.73	134.98	106.02	134.08	101.04	127.78
11.3	102.32	129.43	98.23	124.26	106.27	134.43	105.56	133.53	100.60	127.26
11.4	101.88	128.91	97.81	123.75	105.82	133.89	105.11	132.99	100.17	126.75
11.5	101.44	128.39	97.39	123.25	105.36	133.35	104.65	132.45	99.74	126.23
11.6	101.01	127.87	96.97	122.76	104.91	132.80	104.20	131.91	99.31	125.72
11.7	100.57	127.35	96.56	122.26	104.46	132.27	103.76	131.38	98.88	125.21
11.8	100.14	126.83	96.14	121.77	104.01	131.73	103.31	130.84	98.46	124.70
11.9	99.71	126.32	95.73	121.27	103.56	131.19	102.87	130.31	98.03	124.19
12.0	99.28	125.81	95.32	120.78	103.12	130.66	102.42	129.78	97.61	123.69
12.1	98.86	125.30	94.91	120.30	102.67	130.13	101.98	129.26	97.19	123.18
12.2	98.43	124.79	94.51	119.81	102.23	129.60	101.54	128.73	96.77	122.68
12.3	98.01	124.28	94.10	119.33	101.79	129.08	101.11	128.21	96.36	122.18
12.4	97.59	123.78	93.70	118.84	101.36	128.55	100.67	127.69	95.94	121.69
12.5	97.17	123.28	93.30	118.36	100.92	128.03	100.24	127.17	95.53	121.19
12.6	96.76	122.78	92.90	117.89	100.49	127.51	99.81	126.65	95.12	120.70
12.7	96.34	122.28	92.50	117.41	100.06	126.99	99.38	126.14	94.71	120.21
12.8	95.93	121.78	92.11	116.93	99.63	126.48	98.95	125.62	94.30	119.72
12.9	95.52	121.29	91.71	116.46	99.20	125.97	98.53	125.11	93.90	119.24
13.0	95.11	120.80	91.32	115.99	98.77	125.45	98.10	124.61	93.49	118.75
13.1	94.70	120.31	90.93	115.52	98.35	124.95	97.68	124.10	93.09	118.27
13.2	94.29	119.82	90.54	115.06	97.92	124.44	97.26	123.60	92.69	117.79
13.3	93.89	119.34	90.15	114.59	97.50	123.93	96.84	123.09	92.29	117.31
13.4	93.49	118.85	89.77	114.13	97.08	123.43	96.43	122.59	91.89	116.83
13.5	93.08	118.37	89.38	113.67	96.67	122.93	96.01	122.10	91.50	116.36
13.6	92.69	117.89	89.00	113.21	96.25	122.43	95.60	121.60	91.11	115.88
13.7	92.29	117.42	88.62	112.75	95.84	121.93	95.19	121.11	90.71	115.41
13.8	91.89	116.94	88.24	112.29	95.43	121.44	94.78	120.61	90.32	114.94
13.9	91.50	116.47	87.86	111.84	95.02	120.95	94.37	120.12	89.93	114.48

Table C.2 (continued). RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
14.0	91.10	115.99	87.49	111.39	94.61	120.46	93.97	119.64	89.55	114.01
14.1	90.71	115.52	87.11	110.94	94.20	119.97	93.56	119.15	89.16	113.55
14.2	90.32	115.06	86.74	110.49	93.80	119.48	93.16	118.67	88.78	113.09
14.3	89.94	114.59	86.37	110.04	93.39	118.99	92.76	118.18	88.40	112.63
14.4	89.55	114.13	86.00	109.60	92.99	118.51	92.36	117.70	88.02	112.17
14.5	89.17	113.66	85.63	109.16	92.59	118.03	91.96	117.23	87.64	111.71
14.6	88.79	113.20	85.27	108.72	92.20	117.55	91.57	116.75	87.26	111.26
14.7	88.40	112.74	84.90	108.28	91.80	117.07	91.17	116.28	86.88	110.81
14.8	88.02	112.29	84.54	107.84	91.41	116.60	90.78	115.80	86.51	110.36
14.9	87.65	111.83	84.18	107.40	91.01	116.13	90.39	115.33	86.14	109.91
15.0	87.27	111.38	83.82	106.97	90.62	115.65	90.00	114.86	85.77	109.46
15.1	87.06	111.12	83.61	106.72	90.40	115.39	89.78	114.60	85.56	109.21
15.2	86.85	110.86	83.40	106.47	90.18	115.12	89.56	114.33	85.35	108.96
15.3	86.63	110.61	83.20	106.22	89.96	114.86	89.35	114.07	85.14	108.71
15.4	86.42	110.35	83.00	105.98	89.74	114.59	89.13	113.81	84.94	108.45
15.5	86.21	110.10	82.79	105.73	89.52	114.33	88.91	113.54	84.73	108.20
15.6	86.00	109.84	82.59	105.49	89.30	114.06	88.69	113.28	84.52	107.95
15.7	85.79	109.59	82.39	105.24	89.09	113.80	88.48	113.02	84.32	107.71
15.8	85.58	109.34	82.18	105.00	88.87	113.54	88.26	112.76	84.11	107.46
15.9	85.37	109.08	81.98	104.75	88.65	113.27	88.05	112.50	83.91	107.21
16.0	85.16	108.83	81.78	104.51	88.44	113.01	87.83	112.24	83.70	106.96
16.1	84.96	108.58	81.58	104.27	88.22	112.75	87.62	111.98	83.50	106.72
16.2	84.75	108.33	81.38	104.02	88.00	112.49	87.40	111.72	83.29	106.47
16.3	84.54	108.08	81.18	103.78	87.79	112.23	87.19	111.46	83.09	106.22
16.4	84.34	107.83	80.98	103.54	87.58	111.97	86.98	111.21	82.89	105.98
16.5	84.13	107.58	80.78	103.30	87.36	111.71	86.77	110.95	82.69	105.73
16.6	83.92	107.33	80.58	103.06	87.15	111.45	86.55	110.69	82.49	105.49
16.7	83.72	107.08	80.39	102.82	86.94	111.20	86.34	110.44	82.28	105.25
16.8	83.52	106.84	80.19	102.58	86.72	110.94	86.13	110.18	82.08	105.01
16.9	83.31	106.59	79.99	102.34	86.51	110.68	85.92	109.93	81.88	104.76
17.0	83.11	106.34	79.80	102.11	86.30	110.43	85.71	109.68	81.68	104.52
17.1	82.91	106.10	79.60	101.87	86.09	110.17	85.50	109.42	81.49	104.28
17.2	82.70	105.85	79.41	101.63	85.88	109.92	85.30	109.17	81.29	104.04
17.3	82.50	105.61	79.21	101.39	85.67	109.67	85.09	108.92	81.09	103.80
17.4	82.30	105.36	79.02	101.16	85.46	109.41	84.88	108.67	80.89	103.56
17.5	82.10	105.12	78.82	100.92	85.25	109.16	84.67	108.42	80.69	103.32
17.6	81.90	104.88	78.63	100.69	85.05	108.91	84.47	108.17	80.50	103.08
17.7	81.70	104.63	78.44	100.46	84.84	108.66	84.26	107.92	80.30	102.85
17.8	81.50	104.39	78.24	100.22	84.63	108.41	84.06	107.67	80.11	102.61
17.9	81.30	104.15	78.05	99.99	84.43	108.15	83.85	107.42	79.91	102.37

Table C.2 (continued). RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
18.0	81.10	103.91	77.86	99.76	84.22	107.91	83.65	107.17	79.72	102.14
18.1	80.90	103.67	77.67	99.52	84.01	107.66	83.44	106.92	79.52	101.90
18.2	80.71	103.43	77.48	99.29	83.81	107.41	83.24	106.68	79.33	101.67
18.3	80.51	103.19	77.29	99.06	83.60	107.16	83.04	106.43	79.14	101.43
18.4	80.31	102.95	77.10	98.83	83.40	106.91	82.83	106.18	78.94	101.20
18.5	80.12	102.71	76.91	98.60	83.20	106.66	82.63	105.94	78.75	100.96
18.6	79.92	102.48	76.72	98.37	82.99	106.42	82.43	105.69	78.56	100.73
18.7	79.73	102.24	76.53	98.15	82.79	106.17	82.23	105.45	78.37	100.50
18.8	79.53	102.00	76.34	97.92	82.59	105.93	82.03	105.21	78.18	100.27
18.9	79.34	101.77	76.16	97.69	82.39	105.68	81.83	104.96	77.99	100.04
19.0	79.14	101.53	75.97	97.46	82.19	105.44	81.63	104.72	77.80	99.80
19.1	78.95	101.30	75.78	97.24	81.99	105.20	81.43	104.48	77.61	99.57
19.2	78.76	101.06	75.60	97.01	81.79	104.95	81.23	104.24	77.42	99.34
19.3	78.56	100.83	75.41	96.78	81.59	104.71	81.03	104.00	77.23	99.12
19.4	78.37	100.60	75.23	96.56	81.39	104.47	80.84	103.76	77.04	98.89
19.5	78.18	100.37	75.04	96.34	81.19	104.23	80.64	103.52	76.85	98.66
19.6	77.99	100.13	74.86	96.11	80.99	103.99	80.44	103.28	76.67	98.43
19.7	77.80	99.90	74.67	95.89	80.79	103.75	80.25	103.04	76.48	98.20
19.8	77.61	99.67	74.49	95.67	80.60	103.51	80.05	102.80	76.29	97.98
19.9	77.42	99.44	74.31	95.44	80.40	103.27	79.85	102.57	76.11	97.75
20.0	77.23	99.21	74.13	95.22	80.20	103.03	79.66	102.33	75.92	97.53
20.1	77.04	98.98	73.94	95.00	80.01	102.79	79.47	102.09	75.74	97.30
20.2	76.86	98.75	73.76	94.78	79.81	102.55	79.27	101.86	75.55	97.08
20.3	76.67	98.52	73.58	94.56	79.62	102.32	79.08	101.62	75.37	96.85
20.4	76.48	98.30	73.40	94.34	79.42	102.08	78.89	101.39	75.18	96.63
20.5	76.29	98.07	73.22	94.12	79.23	101.85	78.69	101.15	75.00	96.41
20.6	76.11	97.84	73.04	93.90	79.04	101.61	78.50	100.92	74.82	96.19
20.7	75.92	97.62	72.86	93.68	78.85	101.38	78.31	100.69	74.64	95.96
20.8	75.74	97.39	72.68	93.47	78.65	101.14	78.12	100.45	74.45	95.74
20.9	75.55	97.17	72.51	93.25	78.46	100.91	77.93	100.22	74.27	95.52
21.0	75.37	96.94	72.33	93.03	78.27	100.67	77.74	99.99	74.09	95.30
21.1	75.18	96.72	72.15	92.81	78.08	100.44	77.55	99.76	73.91	95.08
21.2	75.00	96.49	71.97	92.60	77.89	100.21	77.36	99.53	73.73	94.86
21.3	74.82	96.27	71.80	92.38	77.70	99.98	77.17	99.30	73.55	94.64
21.4	74.63	96.05	71.62	92.17	77.51	99.75	76.98	99.07	73.37	94.43
21.5	74.45	95.83	71.44	91.96	77.32	99.52	76.80	98.84	73.19	94.21
21.6	74.27	95.61	71.27	91.74	77.13	99.29	76.61	98.61	73.02	93.99
21.7	74.09	95.38	71.09	91.53	76.94	99.06	76.42	98.39	72.84	93.77
21.8	73.91	95.16	70.92	91.32	76.76	98.83	76.23	98.16	72.66	93.56
21.9	73.73	94.94	70.75	91.10	76.57	98.60	76.05	97.93	72.48	93.34

Table C.2 (continued). RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
22.0	73.55	94.72	70.57	90.89	76.38	98.37	75.86	97.71	72.31	93.13
22.1	73.37	94.51	70.40	90.68	76.19	98.15	75.68	97.48	72.13	92.91
22.2	73.19	94.29	70.23	90.47	76.01	97.92	75.49	97.26	71.95	92.70
22.3	73.01	94.07	70.05	90.26	75.82	97.69	75.31	97.03	71.78	92.48
22.4	72.83	93.85	69.88	90.05	75.64	97.47	75.13	96.81	71.60	92.27
22.5	72.65	93.63	69.71	89.84	75.45	97.24	74.94	96.58	71.43	92.06
22.6	72.48	93.42	69.54	89.63	75.27	97.02	74.76	96.36	71.26	91.84
22.7	72.30	93.20	69.37	89.42	75.09	96.79	74.58	96.14	71.08	91.63
22.8	72.12	92.99	69.20	89.22	74.90	96.57	74.40	95.92	70.91	91.42
22.9	71.95	92.77	69.03	89.01	74.72	96.35	74.21	95.70	70.74	91.21
23.0	71.77	92.56	68.86	88.80	74.54	96.13	74.03	95.48	70.56	91.00
23.1	71.60	92.34	68.69	88.59	74.36	95.90	73.85	95.25	70.39	90.79
23.2	71.42	92.13	68.52	88.39	74.18	95.68	73.67	95.03	70.22	90.58
23.3	71.25	91.92	68.35	88.18	73.99	95.46	73.49	94.82	70.05	90.37
23.4	71.07	91.71	68.19	87.98	73.81	95.24	73.31	94.60	69.88	90.16
23.5	70.90	91.49	68.02	87.77	73.63	95.02	73.14	94.38	69.71	89.96
23.6	70.73	91.28	67.85	87.57	73.45	94.80	72.96	94.16	69.54	89.75
23.7	70.55	91.07	67.68	87.37	73.27	94.58	72.78	93.94	69.37	89.54
23.8	70.38	90.86	67.52	87.16	73.10	94.36	72.60	93.73	69.20	89.34
23.9	70.21	90.65	67.35	86.96	72.92	94.15	72.43	93.51	69.03	89.13
24.0	70.04	90.44	67.19	86.76	72.74	93.93	72.25	93.29	68.86	88.92
24.1	69.87	90.23	67.02	86.56	72.56	93.71	72.07	93.08	68.70	88.72
24.2	69.70	90.02	66.86	86.36	72.39	93.50	71.90	92.86	68.53	88.51
24.3	69.53	89.82	66.69	86.16	72.21	93.28	71.72	92.65	68.36	88.31
24.4	69.36	89.61	66.53	85.96	72.03	93.06	71.55	92.44	68.20	88.11
24.5	69.19	89.40	66.37	85.76	71.86	92.85	71.37	92.22	68.03	87.90
24.6	69.02	89.19	66.20	85.56	71.68	92.63	71.20	92.01	67.86	87.70
24.7	68.85	88.99	66.04	85.36	71.51	92.42	71.02	91.80	67.70	87.50
24.8	68.68	88.78	65.88	85.16	71.33	92.21	70.85	91.58	67.53	87.30
24.9	68.52	88.58	65.72	84.96	71.16	91.99	70.68	91.37	67.37	87.10
25.0	68.35	88.37	65.56	84.76	70.99	91.78	70.51	91.16	67.20	86.89
25.1	68.18	88.17	65.40	84.57	70.81	91.57	70.33	90.95	67.04	86.69
25.2	68.01	87.96	65.24	84.37	70.64	91.36	70.16	90.74	66.88	86.49
25.3	67.85	87.76	65.08	84.17	70.47	91.15	69.99	90.53	66.71	86.29
25.4	67.68	87.56	64.92	83.98	70.30	90.94	69.82	90.32	66.55	86.10
25.5	67.52	87.36	64.76	83.78	70.12	90.73	69.65	90.12	66.39	85.90
25.6	67.35	87.15	64.60	83.59	69.95	90.52	69.48	89.91	66.23	85.70
25.7	67.19	86.95	64.44	83.39	69.78	90.31	69.31	89.70	66.07	85.50
25.8	67.02	86.75	64.28	83.20	69.61	90.10	69.14	89.49	65.91	85.30
25.9	66.86	86.55	64.12	83.01	69.44	89.89	68.97	89.29	65.75	85.11

Table C.2 (continued). RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 0.1 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
26.0	66.70	86.35	63.97	82.81	69.27	89.68	68.81	89.08	65.59	84.91
26.1	66.53	86.15	63.81	82.62	69.10	89.48	68.64	88.87	65.43	84.72
26.2	66.37	85.95	63.65	82.43	68.93	89.27	68.47	88.67	65.27	84.52
26.3	66.21	85.75	63.50	82.24	68.77	89.06	68.30	88.46	65.11	84.33
26.4	66.05	85.56	63.34	82.05	68.60	88.86	68.14	88.26	64.95	84.13
26.5	65.89	85.36	63.18	81.86	68.43	88.65	67.97	88.06	64.79	83.94
26.6	65.73	85.16	63.03	81.67	68.26	88.45	67.81	87.85	64.63	83.74
26.7	65.57	84.96	62.88	81.48	68.10	88.24	67.64	87.65	64.48	83.55
26.8	65.41	84.77	62.72	81.29	67.93	88.04	67.47	87.45	64.32	83.36
26.9	65.25	84.57	62.57	81.10	67.77	87.84	67.31	87.25	64.16	83.17
27.0	65.09	84.38	62.41	80.91	67.60	87.63	67.15	87.04	64.01	82.97
27.1	64.93	84.18	62.26	80.72	67.44	87.43	66.98	86.84	63.85	82.78
27.2	64.77	83.99	62.11	80.53	67.27	87.23	66.82	86.64	63.69	82.59
27.3	64.61	83.79	61.96	80.35	67.11	87.03	66.66	86.44	63.54	82.40
27.4	64.45	83.60	61.80	80.16	66.94	86.83	66.49	86.24	63.38	82.21
27.5	64.30	83.41	61.65	79.97	66.78	86.63	66.33	86.04	63.23	82.02
27.6	64.14	83.21	61.50	79.79	66.62	86.43	66.17	85.85	63.08	81.83
27.7	63.98	83.02	61.35	79.60	66.46	86.23	66.01	85.65	62.92	81.64
27.8	63.83	82.83	61.20	79.42	66.29	86.03	65.85	85.45	62.77	81.45
27.9	63.67	82.64	61.05	79.23	66.13	85.83	65.69	85.25	62.62	81.27
28.0	63.52	82.45	60.90	79.05	65.97	85.63	65.53	85.06	62.46	81.08
28.1	63.36	82.26	60.75	78.87	65.81	85.43	65.37	84.86	62.31	80.89
28.2	63.21	82.07	60.60	78.68	65.65	85.24	65.21	84.66	62.16	80.71
28.3	63.05	81.88	60.45	78.50	65.49	85.04	65.05	84.47	62.01	80.52
28.4	62.90	81.69	60.30	78.32	65.33	84.84	64.89	84.27	61.86	80.33
28.5	62.74	81.50	60.15	78.13	65.17	84.65	64.73	84.08	61.71	80.15
28.6	62.59	81.31	60.01	77.95	65.01	84.45	64.57	83.89	61.56	79.96
28.7	62.44	81.12	59.86	77.77	64.85	84.26	64.42	83.69	61.41	79.78
28.8	62.29	80.93	59.71	77.59	64.69	84.06	64.26	83.50	61.26	79.60
28.9	62.13	80.75	59.57	77.41	64.54	83.87	64.10	83.31	61.11	79.41
29.0	61.98	80.56	59.42	77.23	64.38	83.67	63.95	83.11	60.96	79.23
29.1	61.83	80.37	59.27	77.05	64.22	83.48	63.79	82.92	60.81	79.05
29.2	61.68	80.19	59.13	76.87	64.06	83.29	63.63	82.73	60.66	78.86
29.3	61.53	80.00	58.98	76.69	63.91	83.10	63.48	82.54	60.51	78.68
29.4	61.38	79.82	58.84	76.52	63.75	82.90	63.32	82.35	60.37	78.50
29.5	61.23	79.63	58.69	76.34	63.60	82.71	63.17	82.16	60.22	78.32
29.6	61.08	79.45	58.55	76.16	63.44	82.52	63.02	81.97	60.07	78.14
29.7	60.93	79.27	58.41	75.98	63.29	82.33	62.86	81.78	59.93	77.96
29.8	60.78	79.08	58.26	75.81	63.13	82.14	62.71	81.59	59.78	77.78
29.9	60.63	78.90	58.12	75.63	62.98	81.95	62.56	81.40	59.63	77.60

Table C.2 (continued). RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 0.2 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
30.0	60.49	78.72	57.98	75.45	62.83	81.76	62.40	81.21	59.49	77.42
30.2	60.34	78.57	57.83	75.31	62.68	81.60	62.26	81.05	59.35	77.26
30.4	60.20	78.43	57.69	75.16	62.53	81.43	62.12	80.88	59.22	77.10
30.6	60.05	78.29	57.55	75.01	62.38	81.26	61.97	80.72	59.08	76.94
30.8	59.91	78.14	57.41	74.87	62.24	81.10	61.83	80.55	58.95	76.77
31.0	59.77	78.00	57.26	74.72	62.09	80.93	61.69	80.39	58.81	76.61
31.2	59.63	77.86	57.12	74.58	61.95	80.77	61.54	80.22	58.68	76.45
31.4	59.48	77.72	56.98	74.43	61.80	80.60	61.40	80.06	58.54	76.29
31.6	59.34	77.57	56.84	74.29	61.66	80.44	61.26	79.90	58.41	76.13
31.8	59.20	77.43	56.70	74.14	61.51	80.28	61.12	79.73	58.27	75.97
32.0	59.06	77.29	56.56	74.00	61.37	80.11	60.97	79.57	58.14	75.81
32.2	58.92	77.15	56.42	73.85	61.22	79.95	60.83	79.41	58.01	75.65
32.4	58.78	77.01	56.28	73.71	61.08	79.79	60.69	79.25	57.87	75.50
32.6	58.64	76.87	56.14	73.56	60.93	79.62	60.55	79.09	57.74	75.34
32.8	58.50	76.73	56.00	73.42	60.79	79.46	60.41	78.92	57.61	75.18
33.0	58.36	76.59	55.86	73.28	60.65	79.30	60.27	78.76	57.48	75.02
33.2	58.22	76.45	55.72	73.13	60.51	79.14	60.13	78.60	57.34	74.87
33.4	58.08	76.31	55.59	72.99	60.36	78.98	59.99	78.44	57.21	74.71
33.6	57.94	76.17	55.45	72.85	60.22	78.81	59.85	78.28	57.08	74.55
33.8	57.80	76.03	55.31	72.71	60.08	78.65	59.72	78.12	56.95	74.40
34.0	57.67	75.89	55.17	72.57	59.94	78.49	59.58	77.96	56.82	74.24
34.2	57.53	75.75	55.04	72.42	59.80	78.33	59.44	77.80	56.69	74.08
34.4	57.39	75.61	54.90	72.28	59.66	78.17	59.30	77.64	56.56	73.93
34.6	57.26	75.47	54.76	72.14	59.52	78.02	59.17	77.49	56.43	73.77
34.8	57.12	75.33	54.63	72.00	59.38	77.86	59.03	77.33	56.30	73.62
35.0	56.98	75.20	54.49	71.86	59.24	77.70	58.89	77.17	56.17	73.47
35.2	56.85	75.06	54.36	71.72	59.10	77.54	58.76	77.01	56.04	73.31
35.4	56.71	74.92	54.22	71.58	58.96	77.38	58.62	76.85	55.92	73.16
35.6	56.58	74.79	54.09	71.44	58.82	77.22	58.48	76.70	55.79	73.00
35.8	56.44	74.65	53.96	71.30	58.69	77.07	58.35	76.54	55.66	72.85
36.0	56.31	74.51	53.82	71.16	58.55	76.91	58.21	76.38	55.53	72.70
36.2	56.17	74.38	53.69	71.02	58.41	76.75	58.08	76.23	55.40	72.55
36.4	56.04	74.24	53.56	70.88	58.27	76.60	57.94	76.07	55.28	72.39
36.6	55.91	74.10	53.42	70.75	58.14	76.44	57.81	75.92	55.15	72.24
36.8	55.77	73.97	53.29	70.61	58.00	76.28	57.68	75.76	55.02	72.09
37.0	55.64	73.83	53.16	70.47	57.86	76.13	57.54	75.61	54.90	71.94
37.2	55.51	73.70	53.03	70.33	57.73	75.97	57.41	75.45	54.77	71.79
37.4	55.37	73.56	52.90	70.20	57.59	75.82	57.28	75.30	54.65	71.64
37.6	55.24	73.43	52.77	70.06	57.46	75.66	57.14	75.15	54.52	71.49
37.8	55.11	73.29	52.63	69.92	57.32	75.51	57.01	74.99	54.40	71.34

Table C.2 (continued). RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 0.5 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
38.0	54.98	73.16	52.50	69.79	57.19	75.36	56.88	74.84	54.27	71.19
38.5	54.65	72.83	52.18	69.45	56.85	74.97	56.55	74.46	53.96	70.82
39.0	54.33	72.49	51.86	69.11	56.52	74.59	56.22	74.08	53.65	70.45
39.5	54.00	72.16	51.54	68.77	56.19	74.21	55.90	73.70	53.35	70.08
40.0	53.68	71.83	51.22	68.44	55.86	73.83	55.58	73.33	53.04	69.71
40.5	53.36	71.51	50.90	68.10	55.53	73.46	55.26	72.95	52.74	69.35
41.0	53.05	71.18	50.59	67.77	55.21	73.09	54.94	72.58	52.44	68.98
41.5	52.73	70.85	50.27	67.44	54.88	72.71	54.62	72.21	52.14	68.62
42.0	52.42	70.53	49.96	67.11	54.56	72.34	54.30	71.84	51.84	68.26
42.5	52.11	70.21	49.66	66.79	54.24	71.98	53.99	71.48	51.54	67.91
43.0	51.80	69.89	49.35	66.46	53.93	71.61	53.68	71.11	51.25	67.55
43.5	51.49	69.57	49.04	66.14	53.61	71.25	53.37	70.75	50.95	67.20
44.0	51.18	69.25	48.74	65.82	53.30	70.88	53.06	70.39	50.66	66.85
44.5	50.88	68.94	48.44	65.50	52.98	70.52	52.75	70.03	50.37	66.50
45.0	50.57	68.62	48.14	65.18	52.67	70.16	52.45	69.67	50.08	66.15
45.5	50.27	68.31	47.84	64.86	52.36	69.81	52.15	69.32	49.80	65.80
46.0	49.97	68.00	47.55	64.54	52.06	69.45	51.84	68.97	49.51	65.46
46.5	49.68	67.69	47.25	64.23	51.75	69.10	51.55	68.61	49.23	65.12
47.0	49.38	67.38	46.96	63.92	51.45	68.75	51.25	68.26	48.95	64.78
47.5	49.09	67.07	46.67	63.61	51.15	68.40	50.95	67.92	48.67	64.44
48.0	48.80	66.76	46.38	63.30	50.85	68.05	50.66	67.57	48.39	64.10
48.5	48.51	66.46	46.10	62.99	50.55	67.70	50.36	67.23	48.11	63.77
49.0	48.22	66.15	45.81	62.68	50.25	67.36	50.07	66.88	47.84	63.43
49.5	47.93	65.85	45.53	62.38	49.96	67.02	49.78	66.54	47.56	63.10
50.0	47.65	65.55	45.25	62.07	49.67	66.67	49.50	66.20	47.29	62.77
50.5	47.36	65.25	44.97	61.77	49.38	66.34	49.21	65.87	47.02	62.44
51.0	47.08	64.95	44.69	61.47	49.09	66.00	48.93	65.53	46.75	62.11
51.5	46.80	64.66	44.41	61.17	48.80	65.66	48.64	65.20	46.48	61.79
52.0	46.52	64.36	44.14	60.87	48.51	65.33	48.36	64.86	46.22	61.47
52.5	46.25	64.07	43.87	60.58	48.23	65.00	48.08	64.53	45.95	61.15
53.0	45.97	63.78	43.59	60.28	47.95	64.67	47.81	64.20	45.69	60.83
53.5	45.70	63.49	43.32	59.99	47.67	64.34	47.53	63.88	45.43	60.51
54.0	45.42	63.20	43.06	59.69	47.39	64.01	47.26	63.55	45.17	60.19
54.5	45.15	62.91	42.79	59.40	47.11	63.68	46.98	63.23	44.91	59.88
55.0	44.89	62.62	42.53	59.11	46.83	63.36	46.71	62.91	44.65	59.56
55.5	44.62	62.33	42.26	58.83	46.56	63.04	46.44	62.59	44.40	59.25
56.0	44.35	62.05	42.00	58.54	46.29	62.72	46.17	62.27	44.14	58.94
56.5	44.09	61.77	41.74	58.26	46.01	62.40	45.91	61.95	43.89	58.63
57.0	43.83	61.48	41.49	57.97	45.74	62.08	45.64	61.63	43.64	58.33
57.5	43.57	61.20	41.23	57.69	45.48	61.76	45.38	61.32	43.39	58.02

Table C.2 (continued). RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 1.0 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
58.0	43.31	60.92	40.97	57.41	45.21	61.45	45.12	61.01	43.14	57.72
59.0	42.79	60.37	40.47	56.85	44.68	60.83	44.60	60.39	42.65	57.12
60.0	42.29	59.82	39.97	56.30	44.16	60.21	44.08	59.77	42.16	56.52
61.0	41.92	59.30	39.64	55.83	43.78	59.71	43.70	59.27	41.79	56.05
62.0	41.57	58.79	39.30	55.37	43.41	59.21	43.32	58.78	41.43	55.58
63.0	41.21	58.29	38.98	54.92	43.04	58.72	42.94	58.28	41.06	55.12
64.0	40.86	57.79	38.65	54.46	42.68	58.23	42.57	57.80	40.70	54.66
65.0	40.51	57.29	38.33	54.01	42.31	57.74	42.19	57.31	40.35	54.20
66.0	40.16	56.80	38.01	53.57	41.95	57.26	41.83	56.83	39.99	53.75
67.0	39.82	56.31	37.69	53.13	41.60	56.79	41.46	56.36	39.64	53.30
68.0	39.48	55.83	37.37	52.69	41.24	56.31	41.10	55.88	39.29	52.86
69.0	39.14	55.35	37.06	52.25	40.89	55.84	40.74	55.42	38.95	52.42
70.0	38.80	54.87	36.75	51.82	40.54	55.38	40.39	54.95	38.60	51.98
71.0	38.47	54.40	36.44	51.39	40.20	54.92	40.04	54.49	38.27	51.55
72.0	38.14	53.93	36.14	50.97	39.86	54.46	39.69	54.03	37.93	51.12
73.0	37.81	53.47	35.84	50.55	39.52	54.01	39.34	53.58	37.60	50.69
74.0	37.49	53.01	35.54	50.13	39.18	53.56	39.00	53.13	37.27	50.27
75.0	37.17	52.55	35.24	49.72	38.85	53.11	38.66	52.69	36.94	49.85
76.0	36.85	52.10	34.94	49.31	38.52	52.67	38.32	52.25	36.62	49.44
77.0	36.54	51.65	34.65	48.90	38.19	52.23	37.99	51.81	36.29	49.03
78.0	36.22	51.21	34.36	48.50	37.86	51.79	37.66	51.38	35.98	48.62
79.0	35.91	50.77	34.07	48.10	37.54	51.36	37.33	50.95	35.66	48.21
80.0	35.61	50.33	33.79	47.70	37.22	50.93	37.00	50.52	35.35	47.81
81.0	35.30	49.90	33.51	47.31	36.91	50.51	36.68	50.10	35.04	47.41
82.0	35.00	49.47	33.23	46.91	36.59	50.09	36.36	49.68	34.73	47.02
83.0	34.70	49.04	32.95	46.53	36.28	49.67	36.04	49.26	34.42	46.63
84.0	34.40	48.62	32.67	46.14	35.97	49.26	35.73	48.85	34.12	46.24
85.0	34.11	48.20	32.40	45.76	35.67	48.85	35.42	48.44	33.82	45.85
86.0	33.81	47.79	32.13	45.38	35.36	48.44	35.11	48.03	33.52	45.47
87.0	33.53	47.38	31.86	45.01	35.06	48.04	34.80	47.63	33.23	45.09
88.0	33.24	46.97	31.59	44.64	34.76	47.64	34.50	47.23	32.94	44.72
89.0	32.95	46.57	31.33	44.27	34.47	47.24	34.20	46.84	32.65	44.34
90.0	32.67	46.17	31.07	43.91	34.17	46.85	33.90	46.44	32.36	43.97
91.0	32.39	45.77	30.81	43.54	33.88	46.46	33.61	46.05	32.08	43.61
92.0	32.11	45.38	30.55	43.18	33.59	46.07	33.31	45.67	31.80	43.24
93.0	31.84	44.99	30.29	42.83	33.31	45.69	33.02	45.29	31.52	42.88
94.0	31.57	44.60	30.04	42.47	33.03	45.31	32.74	44.91	31.24	42.53
95.0	31.30	44.22	29.79	42.12	32.74	44.93	32.45	44.53	30.97	42.17
96.0	31.03	43.84	29.54	41.78	32.47	44.55	32.17	44.16	30.69	41.82
97.0	30.76	43.46	29.29	41.43	32.19	44.18	31.89	43.79	30.43	41.47
98.0	30.50	43.08	29.05	41.09	31.92	43.81	31.61	43.42	30.16	41.13

Table C.2 (continued). RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 2.0 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
100.0	29.98	42.35	28.56	40.41	31.37	43.09	31.06	42.70	29.63	40.44
102.0	29.47	41.62	28.09	39.75	30.84	42.37	30.52	41.99	29.11	39.77
104.0	28.97	40.91	27.62	39.10	30.32	41.67	29.99	41.28	28.60	39.11
106.0	28.47	40.21	27.16	38.45	29.81	40.98	29.47	40.60	28.10	38.46
108.0	27.99	39.52	26.71	37.82	29.30	40.30	28.96	39.92	27.61	37.83
110.0	27.51	38.84	26.26	37.20	28.81	39.63	28.46	39.25	27.13	37.20
112.0	27.04	38.18	25.82	36.59	28.32	38.97	27.96	38.60	26.66	36.58
114.0	26.58	37.52	25.39	35.99	27.84	38.33	27.48	37.95	26.19	35.97
116.0	26.13	36.88	24.97	35.39	27.37	37.69	27.00	37.32	25.73	35.38
118.0	25.68	36.25	24.55	34.81	26.90	37.06	26.53	36.70	25.28	34.79
120.0	25.24	35.63	24.15	34.24	26.45	36.45	26.07	36.09	24.84	34.21
122.0	24.98	35.16	23.89	33.79	26.17	36.00	25.80	35.63	24.58	33.79
124.0	24.73	34.70	23.64	33.34	25.91	35.55	25.54	35.19	24.33	33.37
126.0	24.47	34.24	23.39	32.90	25.64	35.11	25.27	34.75	24.08	32.95
128.0	24.22	33.79	23.15	32.46	25.38	34.68	25.01	34.31	23.83	32.54
130.0	23.97	33.35	22.91	32.03	25.12	34.25	24.76	33.88	23.59	32.14
132.0	23.73	32.91	22.67	31.61	24.86	33.82	24.50	33.46	23.35	31.74
134.0	23.48	32.47	22.43	31.19	24.60	33.40	24.25	33.04	23.10	31.35
136.0	23.24	32.05	22.19	30.78	24.35	32.99	24.00	32.62	22.87	30.96
138.0	23.00	31.62	21.96	30.37	24.10	32.58	23.75	32.22	22.63	30.57
140.0	22.77	31.21	21.73	29.97	23.86	32.18	23.50	31.81	22.40	30.19
142.0	22.53	30.80	21.50	29.57	23.61	31.78	23.26	31.41	22.17	29.82
144.0	22.30	30.39	21.28	29.18	23.37	31.38	23.02	31.02	21.94	29.45
146.0	22.07	29.99	21.05	28.79	23.13	31.00	22.78	30.63	21.72	29.08
148.0	21.85	29.60	20.83	28.41	22.89	30.61	22.55	30.25	21.49	28.72
150.0	21.62	29.21	20.61	28.03	22.66	30.23	22.32	29.87	21.27	28.37
152.0	21.40	28.82	20.40	27.66	22.43	29.86	22.09	29.49	21.05	28.01
154.0	21.18	28.44	20.18	27.29	22.20	29.49	21.86	29.12	20.84	27.67
156.0	20.96	28.07	19.97	26.93	21.97	29.12	21.63	28.76	20.62	27.32
158.0	20.75	27.70	19.76	26.58	21.74	28.76	21.41	28.40	20.41	26.98
160.0	20.54	27.34	19.56	26.22	21.52	28.41	21.19	28.04	20.20	26.65
162.0	20.33	26.98	19.35	25.88	21.30	28.05	20.97	27.69	19.99	26.32
164.0	20.12	26.62	19.15	25.53	21.08	27.71	20.75	27.34	19.79	25.99
166.0	19.91	26.27	18.95	25.20	20.86	27.36	20.54	27.00	19.58	25.67
168.0	19.71	25.92	18.75	24.86	20.65	27.02	20.33	26.66	19.38	25.35

Table C.2 (continued). RAINFALL INTENSITY - DURATION METRIC TABLES

TIME INTERVAL ON THIS SHEET = 2.0 MINUTES
Rainfall Intensity given in millimeters per hour.

Time in	Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
Minutes	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year	10 year	50 year
170.0	19.50	25.58	18.55	24.53	20.44	26.69	20.12	26.33	19.18	25.03
172.0	19.30	25.25	18.36	24.21	20.23	26.36	19.91	26.00	18.98	24.72
174.0	19.11	24.91	18.16	23.89	20.02	26.03	19.71	25.67	18.79	24.42
176.0	18.91	24.59	17.97	23.57	19.82	25.71	19.50	25.35	18.60	24.11
178.0	18.72	24.26	17.78	23.26	19.61	25.39	19.30	25.03	18.40	23.81
180.0	18.52	23.94	17.60	22.95	19.41	25.08	19.10	24.72	18.21	23.52
182.0	18.41	23.82	17.49	22.83	19.30	24.95	18.98	24.59	18.10	23.39
184.0	18.30	23.69	17.38	22.71	19.18	24.82	18.87	24.46	17.99	23.26
186.0	18.18	23.57	17.27	22.59	19.07	24.69	18.75	24.33	17.88	23.14
188.0	18.07	23.45	17.16	22.47	18.95	24.56	18.63	24.20	17.76	23.01
190.0	17.96	23.33	17.05	22.35	18.84	24.44	18.52	24.07	17.65	22.89
192.0	17.85	23.21	16.94	22.23	18.73	24.31	18.40	23.94	17.54	22.76
194.0	17.74	23.09	16.83	22.11	18.62	24.18	18.29	23.81	17.43	22.64
196.0	17.63	22.97	16.73	22.00	18.51	24.06	18.18	23.68	17.32	22.52
198.0	17.52	22.85	16.62	21.88	18.40	23.93	18.06	23.56	17.22	22.39
200.0	17.41	22.73	16.52	21.76	18.29	23.81	17.95	23.43	17.11	22.27
202.0	17.30	22.61	16.41	21.65	18.18	23.69	17.84	23.31	17.00	22.15
204.0	17.20	22.49	16.31	21.53	18.07	23.57	17.73	23.18	16.90	22.03
206.0	17.09	22.38	16.21	21.42	17.96	23.44	17.62	23.06	16.79	21.91
208.0	16.98	22.26	16.10	21.31	17.85	23.32	17.51	22.93	16.68	21.79
210.0	16.88	22.14	16.00	21.19	17.75	23.20	17.40	22.81	16.58	21.68
212.0	16.77	22.03	15.90	21.08	17.64	23.08	17.30	22.69	16.48	21.56
214.0	16.67	21.92	15.80	20.97	17.54	22.96	17.19	22.57	16.37	21.44
216.0	16.57	21.80	15.70	20.86	17.43	22.85	17.08	22.45	16.27	21.32
218.0	16.47	21.69	15.60	20.75	17.33	22.73	16.98	22.33	16.17	21.21
220.0	16.36	21.58	15.50	20.64	17.23	22.61	16.87	22.21	16.07	21.09
222.0	16.26	21.46	15.40	20.53	17.12	22.49	16.77	22.09	15.97	20.98
224.0	16.16	21.35	15.31	20.42	17.02	22.38	16.66	21.97	15.87	20.87
226.0	16.06	21.24	15.21	20.31	16.92	22.26	16.56	21.85	15.77	20.75
228.0	15.96	21.13	15.11	20.20	16.82	22.15	16.46	21.74	15.67	20.64
230.0	15.86	21.02	15.02	20.10	16.72	22.03	16.36	21.62	15.57	20.53
232.0	15.77	20.91	14.92	19.99	16.62	21.92	16.26	21.51	15.48	20.42
234.0	15.67	20.80	14.83	19.89	16.52	21.81	16.16	21.39	15.38	20.31
236.0	15.57	20.70	14.73	19.78	16.42	21.69	16.06	21.28	15.28	20.19
238.0	15.48	20.59	14.64	19.68	16.33	21.58	15.96	21.16	15.19	20.09
240.0	15.38	20.48	14.55	19.57	16.23	21.47	15.86	21.05	15.09	19.98

Appendix D Selected Isopluvial Maps

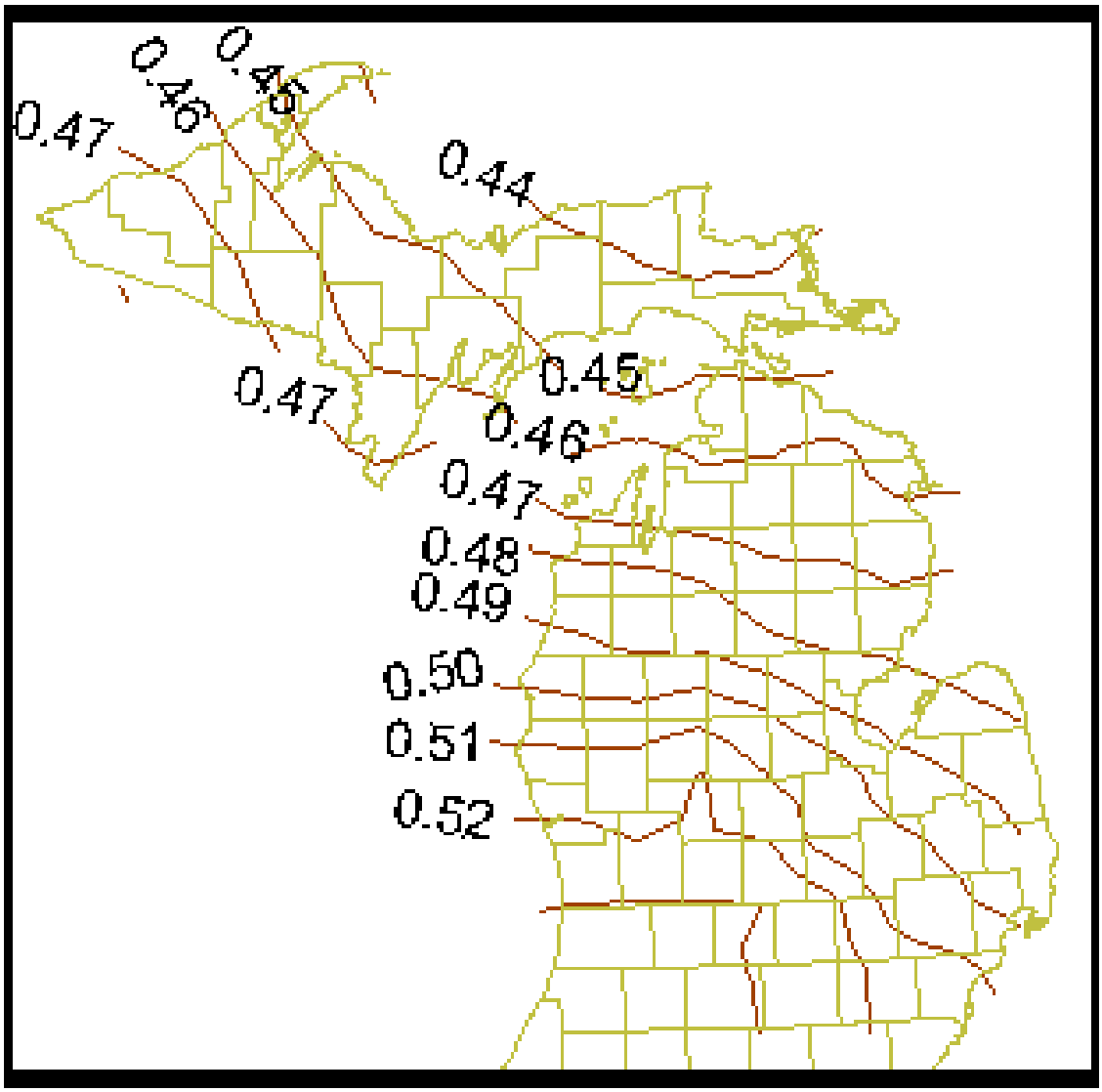

Figure D.1: Isopluvial Map of 2-Year, 10-Minute Rainfall Intensity

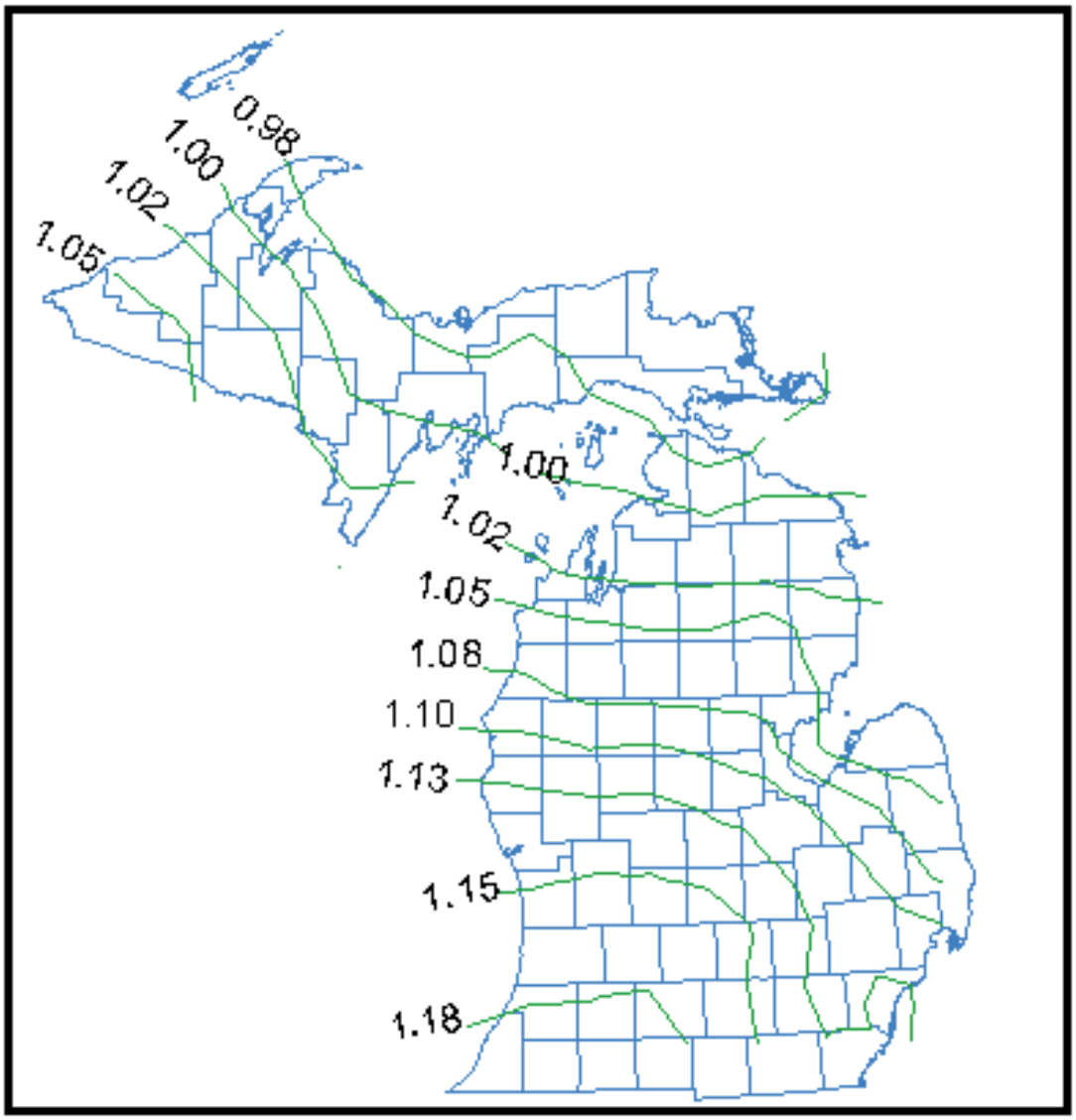

Figure D.2: Isopluvial Map of 2-Year, 1-Hour Rainfall Intensity

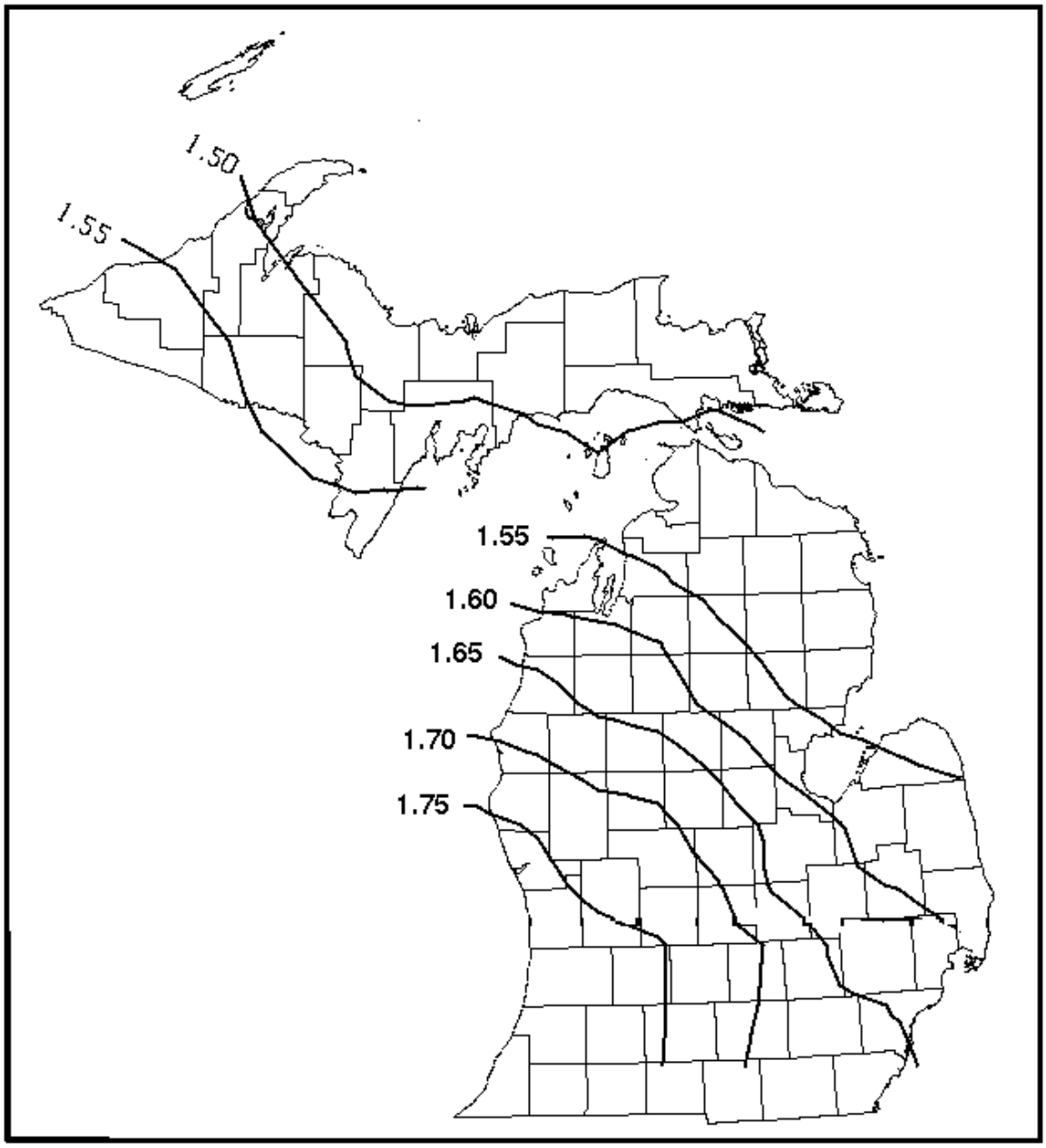

Figure D.3: Isopluvial Map of 2-Year, 6-Hour Rainfall Intensity

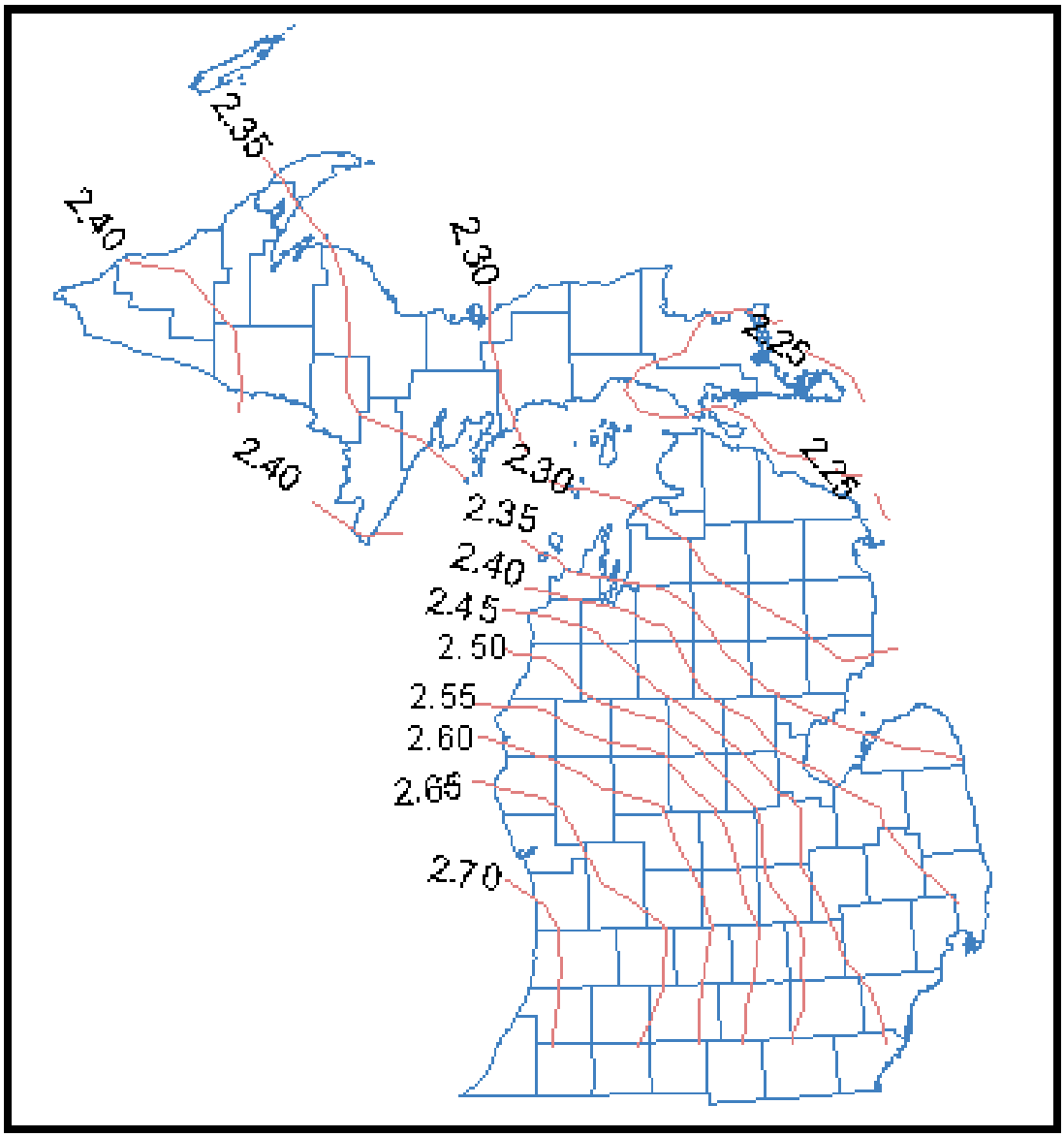

Figure D.4: Isopluvial Map of 2-Year, 24-Hour Rainfall Intensity

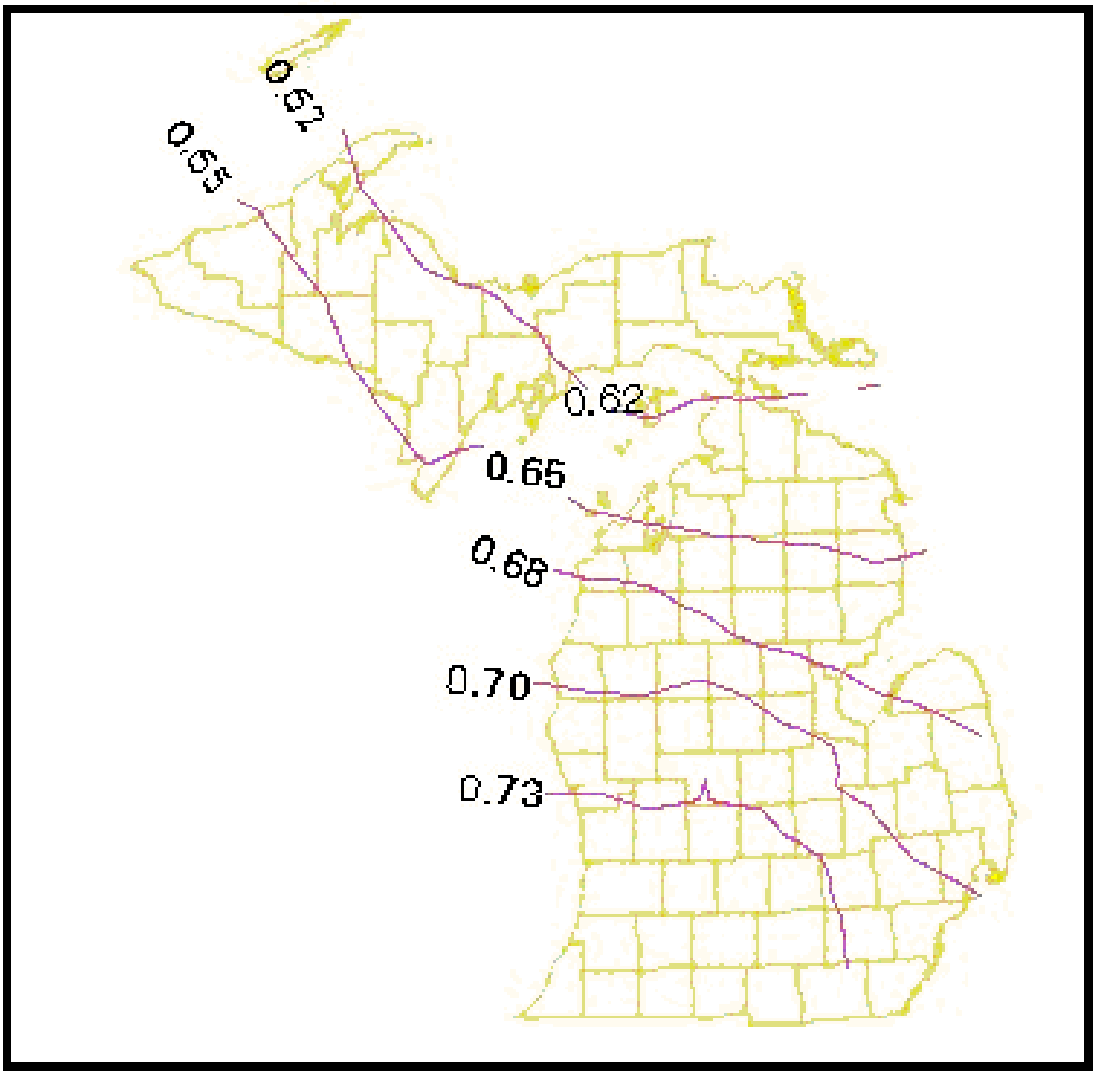

Figure D.5: Isopluvial Map of 10-Year, 10-Minute Rainfall Intensity

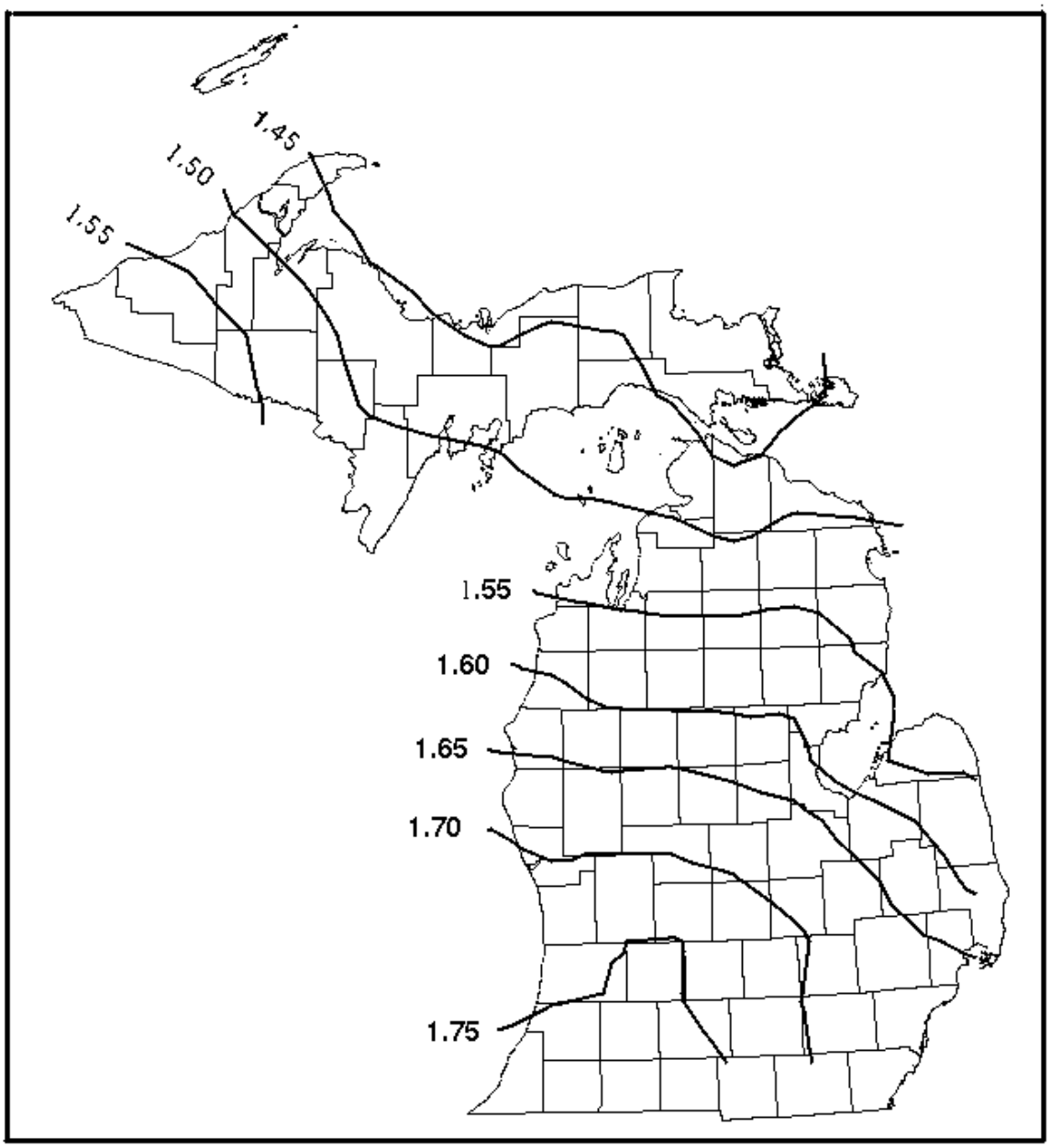

Figure D.6: Isopluvial Map of 10-Year, 1-Hour Rainfall Intensity

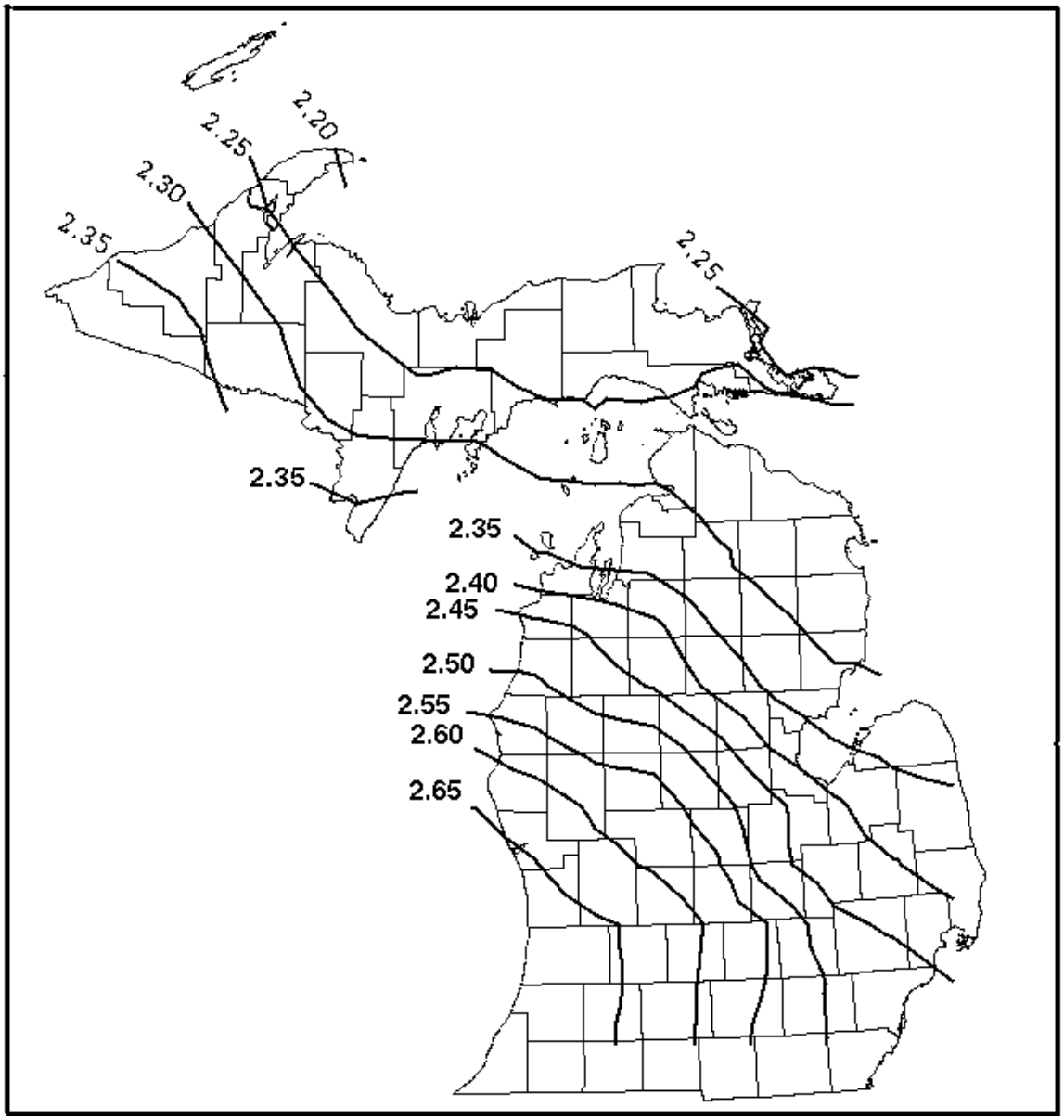

Figure D.7: Isopluvial Map of 10-Year, 6-Hour Rainfall Intensity

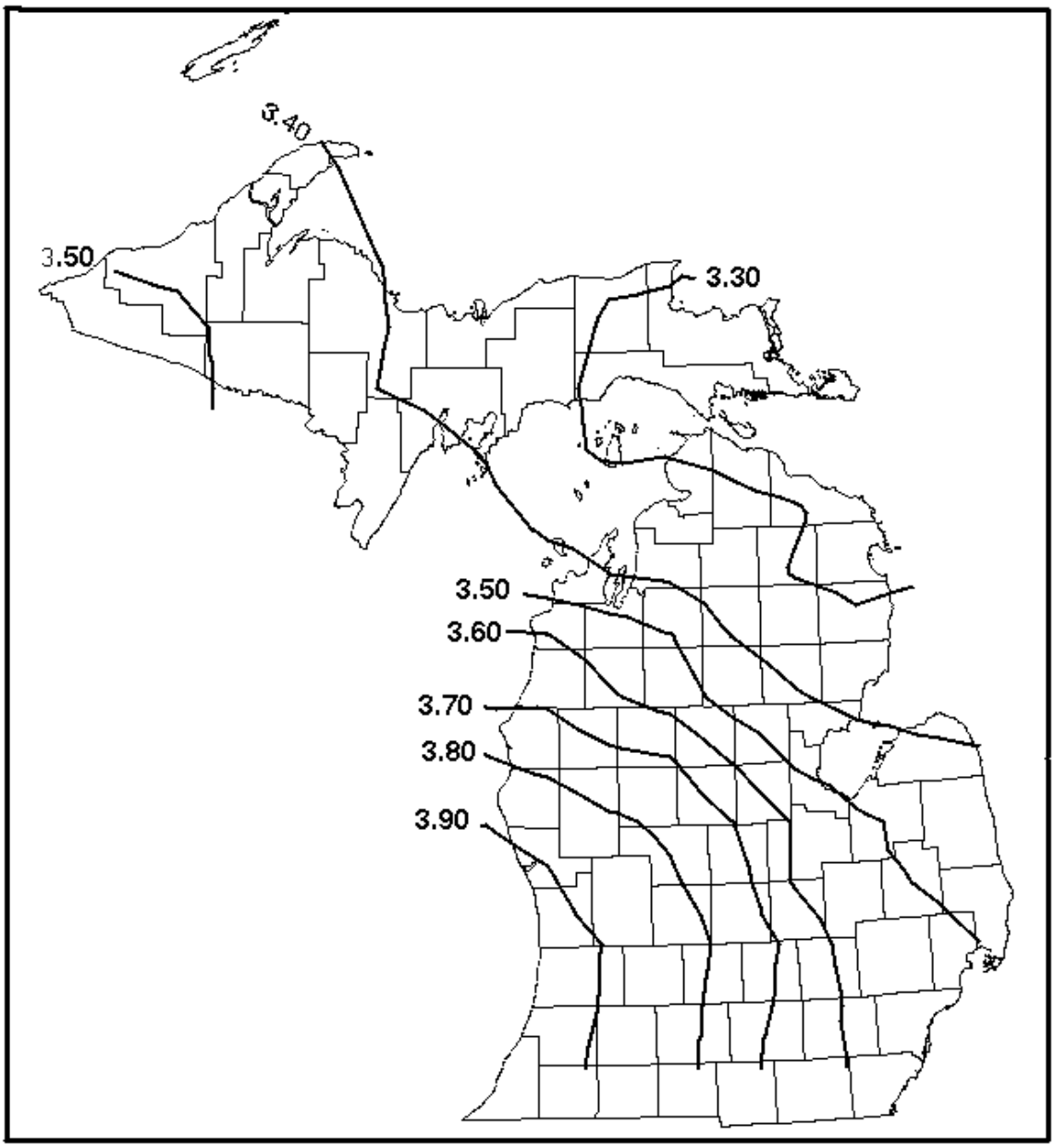

Figure D.8: Isopluvial Map of 10-Year, 24-Hour Rainfall Intensity

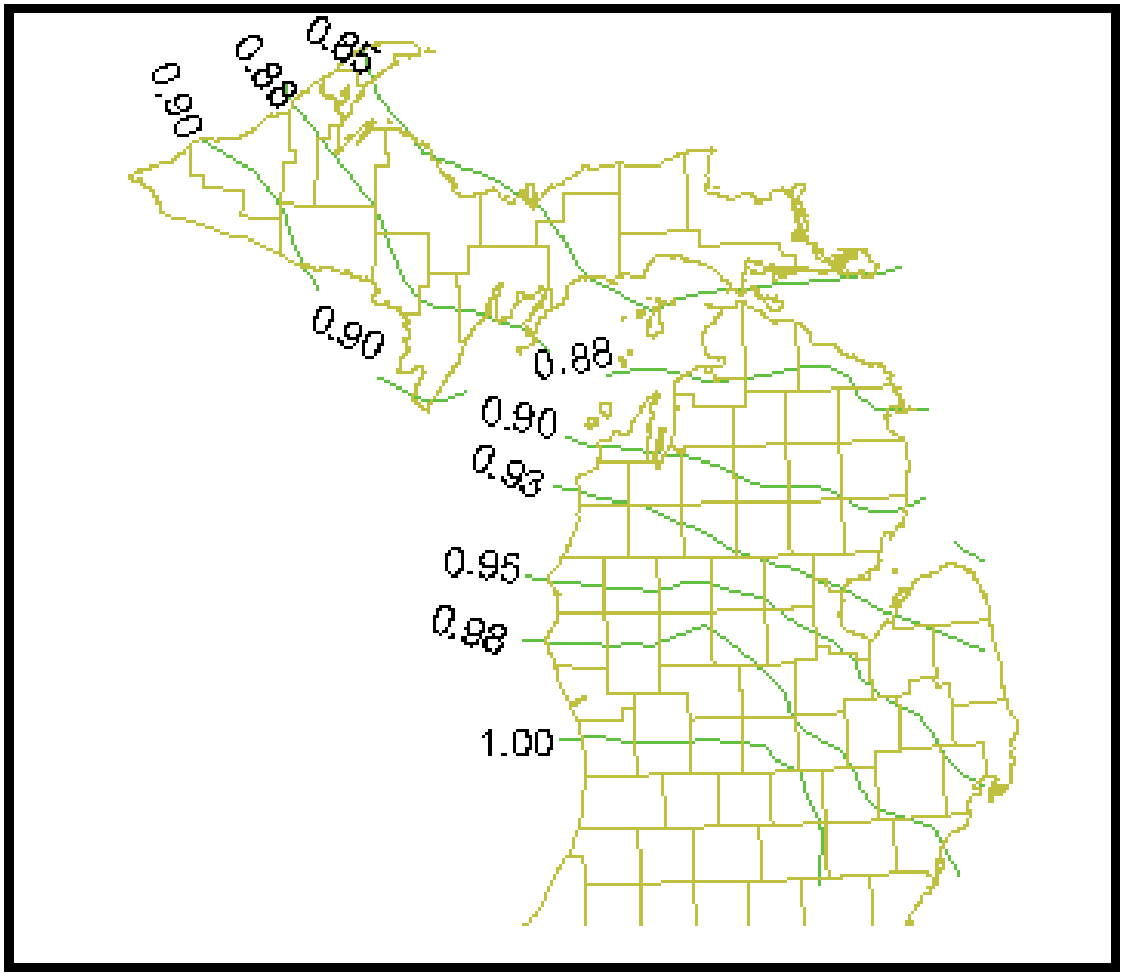

Figure D.9: Isopluvial Map of 100-Year, 10-Minute Rainfall Intensity

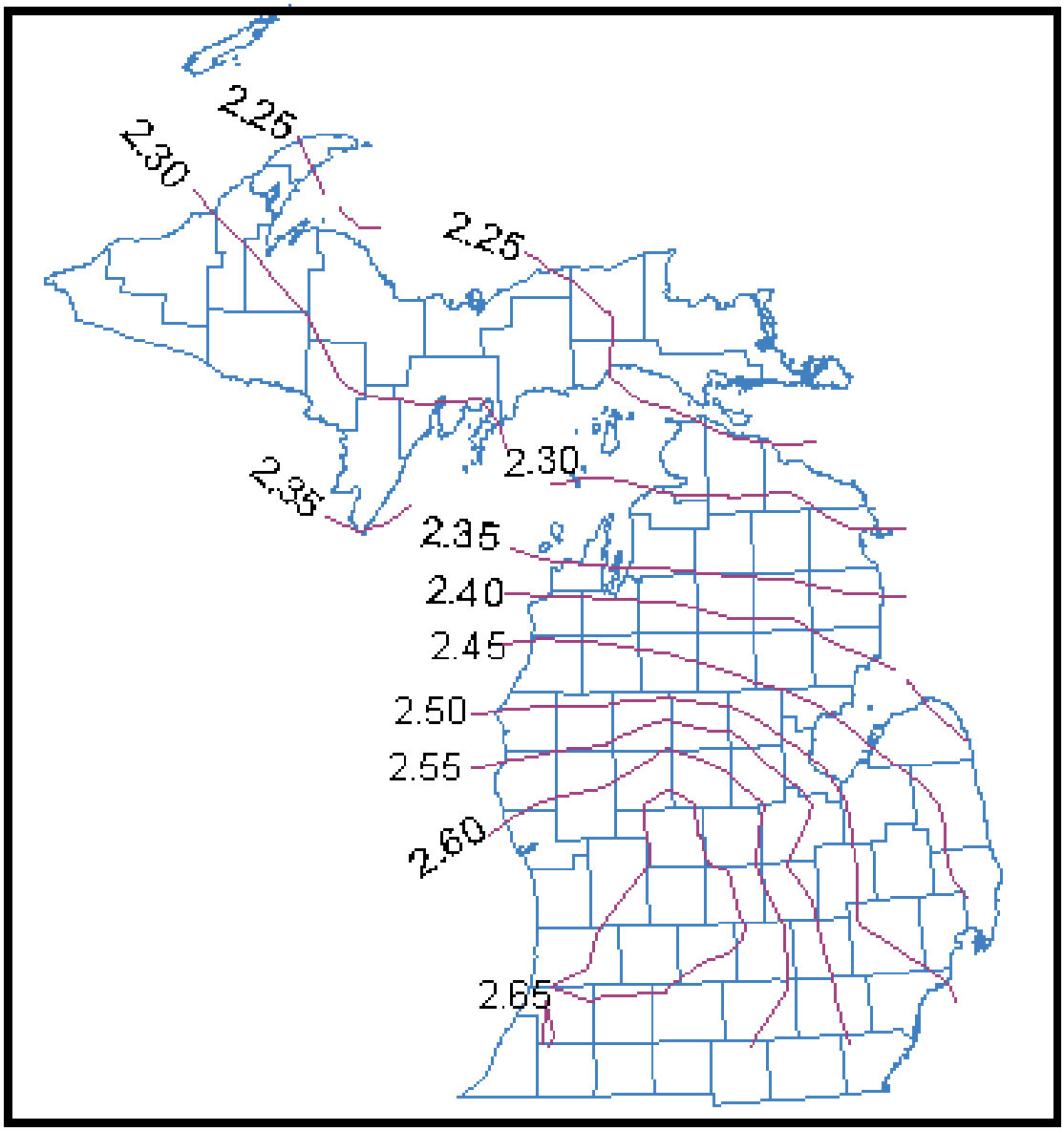

Figure D.10: Isopluvial Map of 100-Year, 1-Hour Rainfall Intensity

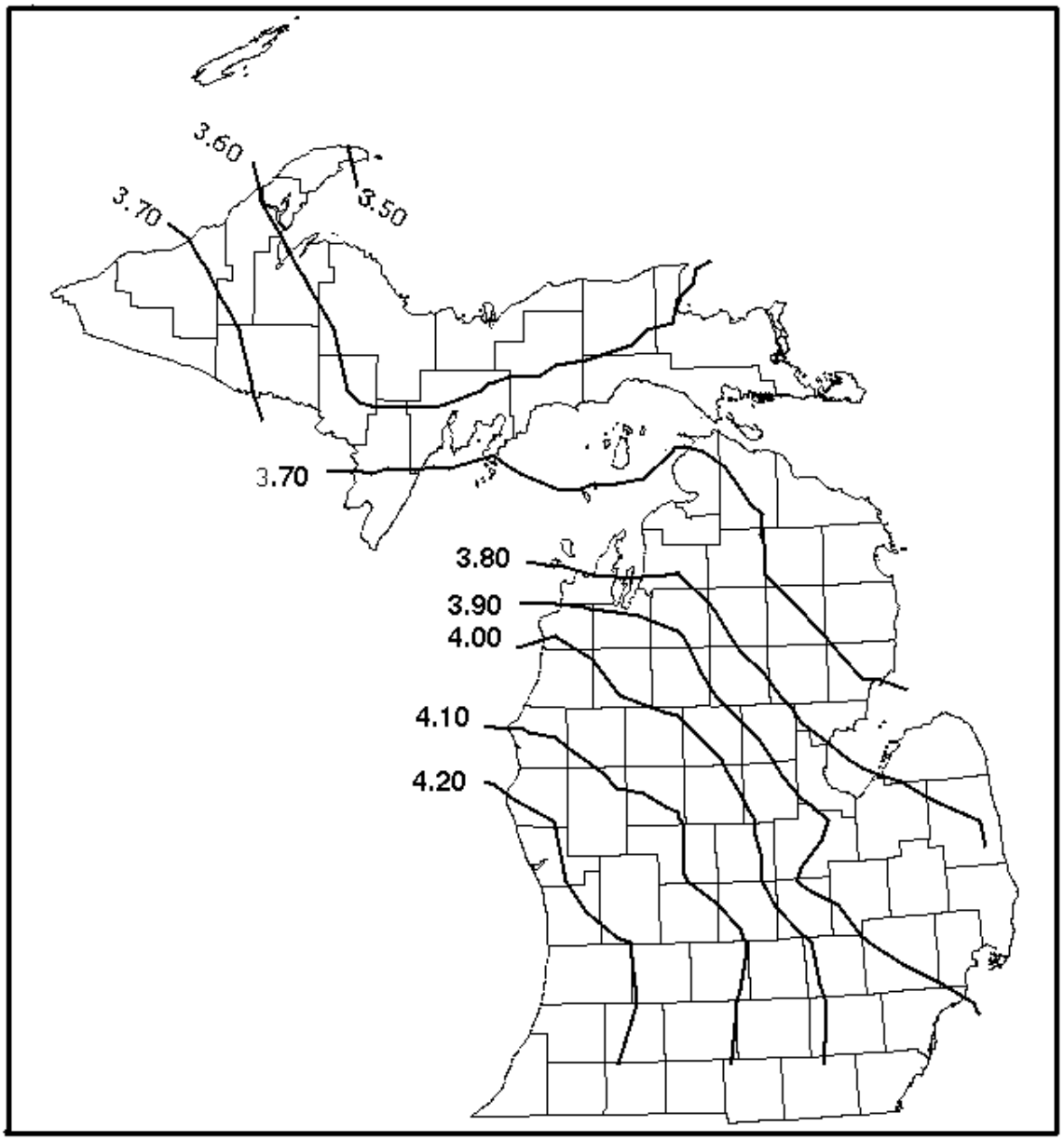

Figure D.11: Isopluvial Map of 100-Year, 6-Hour Rainfall Intensity

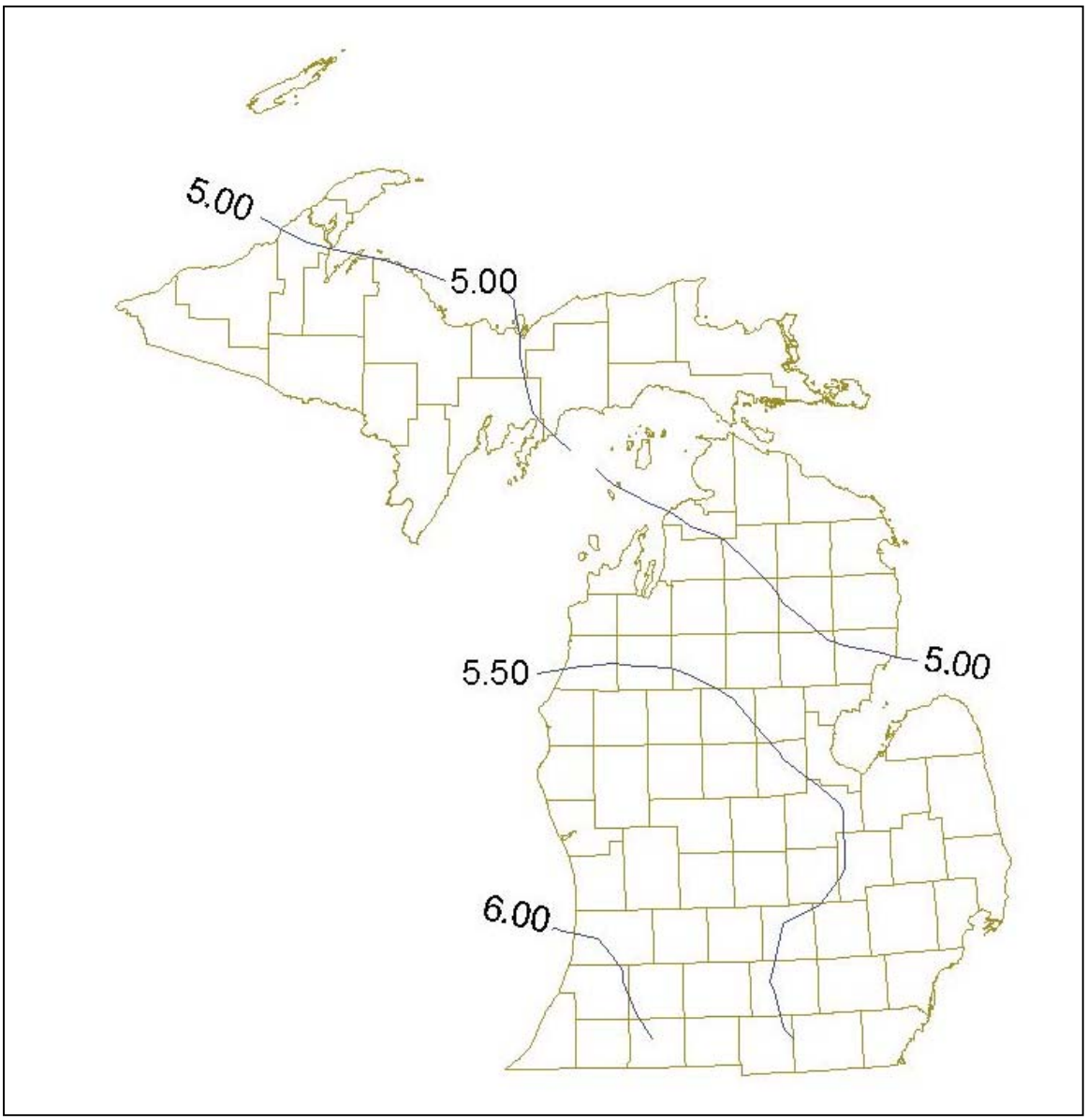

Figure D.12: Isopluvial Map of 100-Year, 24-Hour Rainfall Intensity

Appendix E Kriging Theory and Results

E.1 Mathematical Basis of Kriging

Kriging, like other linear estimation methods, models the spatial behavior of a random variable, such as rainfall IDF estimates, by estimating unknown values from a weighted average of observed values. However, unlike other methods, kriging determines the weighted average based on the orientation (*i.e.*, distance and direction) of the observed point values with respect to the unknown value location. Thus, kriging more appropriately describes/measures the similarity between an unknown location and neighboring observations (Clark 1987). Based on several underlying assumptions, the weights are assigned so that the sum of the weights equals to 1 (*i.e.*, unbiased estimate). Kriging is advantageous over other methods because: 1) its results are reproducible; 2) it relies on an explicit model of spatial variability; 3) it provides "best" estimates and measures of the reliability of the estimates; and 4) it is less labor-intensive and more objective than other methods (Kitanidis 1993).

The process of geostatistical linear estimation involves two main steps: structural analysis and best linear unbiased estimation (BLUE). In general, structural analysis is the identification of a theoretical semivariogram model used to characterize the spatial variability in the variable of interest. BLUE uses the semivariogram model parameters to determine the interpolated estimates, which are unbiased and have a minimum variance.

In the initial assessment of the six spatial interpolation algorithms, only brief descriptions of geostatistics, ordinary kriging, and the semivariogram were given. This section will review, in more detail, ordinary kriging by focusing on underlying statistical assumptions, the semivariogram, and on the assignment of weights used in the kriging

process. In addition, spatial averaging of point estimates through block kriging will be discussed.

E.1.1 Underlying Statistical Assumptions of Ordinary Kriging

In general linear estimation, the spatial variable of interest represents a collection of random values distributed over space or time as described by a random function. In geostatistics, the random function is assumed to be characterized by three components: 1) a structural component, having a constant mean or trend; 2) a random, but spatially correlated component, *i.e.*, regionalized variable; and 3) a spatially uncorrelated component (random noise or residual error) (Burrough and McDonnell 1998). This characterization of the random function is known as the regionalized variable theory, which is the foundation of geostatistics (Armstrong 1998). Equation E.1 illustrates the mathematical representation of the regionalized variable theory (Burrough and McDonnell 1998).

$$Z(x) = m(x) + \varepsilon'(x) + \varepsilon'' \tag{E.1}$$

Letting x represent the position in 1, 2, or 3 dimensions, Z is a random variable at x, $m(x)$ is the structural component of Z at x, $\varepsilon'(x)$ is the regionalized variable, and $\varepsilon''(x)$ is the spatially uncorrelated component. Figure E.1 illustrates the three components that characterize the regionalized variable theory.

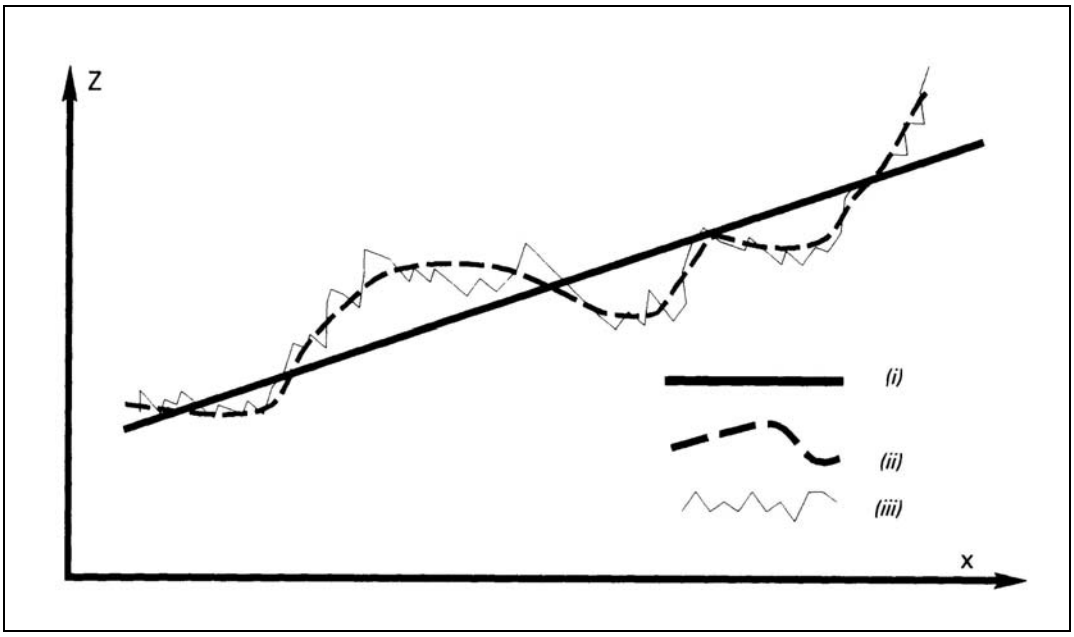

Figure E.1. Three components of the regionalized variable theory, where (i) is the structural component; (ii) is the random, but spatially correlated component; and (iii) is the spatially uncorrelated component (Burrough and McDonnell 1998).

The spatial variable is referred to as a regionalized variable and initially assumed stationary (Hohn 1988). The concept of stationarity infers that all moments of the variable are homogeneous and self-repeating in space or time (Armstrong 1998). Since strict stationarity cannot typically be verified due to a lack of sampled data, only the mean and covariance are typically required to be constant, a condition termed "second order stationarity" (Armstrong 1998). If the regionalized variable is unable to satisfy second order stationarity, a less restrictive condition is the intrinsic hypothesis, which only restricts the first moment, *i.e.* mean, to be constant with respect to its position (Hohn 1988). Under the intrinsic hypothesis, the following assumptions can be made: 1) $m(x)$ equals the mean value of the sampling area; 2) the average or expected difference between any two locations x and $x + h$, separated by a distance vector h, will be zero; and 3) the variance of difference depends only on the distance h between sites (Burrough and

McDonnell 1998). The two assumptions are known as the stationarity of difference and variance of differences, respectively.

$$E[Z(x) - Z(x+h)] = 0 \tag{E.2}$$

$$E[\{Z(x) - Z(x+h)\}^2] = 2\gamma(h) \tag{E.3}$$

where $\gamma(h)$ is known as the semivariance. The intrinsic hypothesis states that once structural effects have been accounted for, the remaining variation is homogeneous, *i.e.*, differences between sites are only a function of distance (Armstrong 1998). Equation E.4 illustrates the equivalence between $\varepsilon'(x)$ and $\gamma(h)$ by rewriting Equation E.1.

$$Z(x) = m(x) + \gamma(h) + \varepsilon'' \tag{E.4}$$

By definition of the intrinsic hypothesis, Equation E.5 is the mathematical definition of the experimental semivariogram ($\hat{\gamma}(h)$) and can be used to estimate the expected difference in value between pairs of samples with a given relative orientation (Clark 1987).

$$\hat{\gamma}(h) = \frac{1}{2n}\sum_{i=1}^{n}\{z(x_i) - z(x_i + h)\}^2 \tag{E.5}$$

where n is the number of observations in the sample of the attribute z separated by distance h, known as the lag distance.

Prior to calculating the semivariance of the sample data, an appropriate range of lag distances must be identified (similar to bin size in a histogram). The range in lag distances should be no greater than one half the width of the area being sampled and no less than the smallest sampling distance to ensure that each lag distance contains at least 3 or 4 calculated semivariance values (Burrough and McDonnell 1998; Hohn 1988). A lag distance approximately equal to the average sample spacing would be an acceptable

initial lag distance (Armstrong 1998). The graphical form of the semivariogram, as shown in Figure E.2, is commonly used to assist in the selection of appropriate control parameters, such as the range and lag distance.

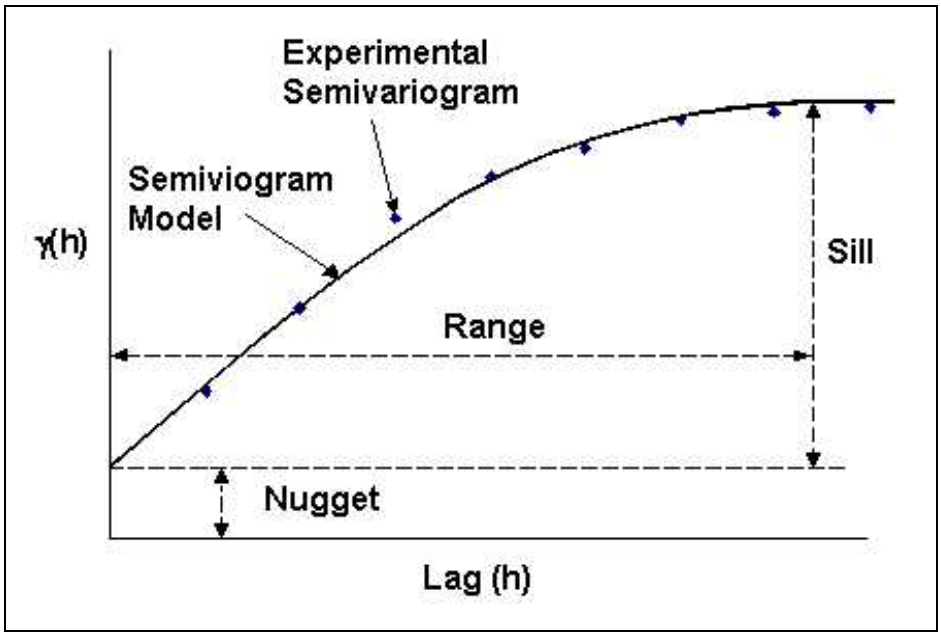

Figure E.2. An example of a semivariogram model fitted to the experimental semivariogram, with identification of the nugget, range, and sill.

E.1.2 The Semivariogram

The semivariogram is the fundamental geostatistical tool for describing the spatial variation of a regionalized variable, and it is used in determining the weights that provide minimum estimation variance (Hohn 1988; Cressie 1991). The construction of the semivariogram involves an interactive investigation to quantitatively describe the spatial variation of the regionalized variable (Burrough and McDonnell 1998). Presenting the experimental semivariogram in graphical form allows for a thorough examination of the spatial variation of the samples prior to fitting a theoretical semivariogram model to the experimental semivariogram. The examination should investigate the stability of the

semivariogram and presence of anisotropic effects that may be characteristic of the regionalized variable.

The stability of experimental semivariogram can be investigated through an iterative process of recalculating the experimental semivariogram at several lag distances within the previously identified range. The experimental semivariogram may be considered stable or well behaved if the position of the semivariogram between the origin and the sill remains relatively stationary (*i.e.*, there is little fluctuation in the vertical direction) while the lag distance changes. For matters of convenience, the stability of the semivariogram should be investigated assuming isotropic conditions, whereby the covariance function depends only on the separation distance and all directional effects are ignored (Kitanidis 1993). In this case, the calculated semivariogram is actually the average semivariogram over all directions (Burrough and McDonnell 1998). Figure E.3 illustrates the shape of the neighborhood search radius assuming isotropic conditions.

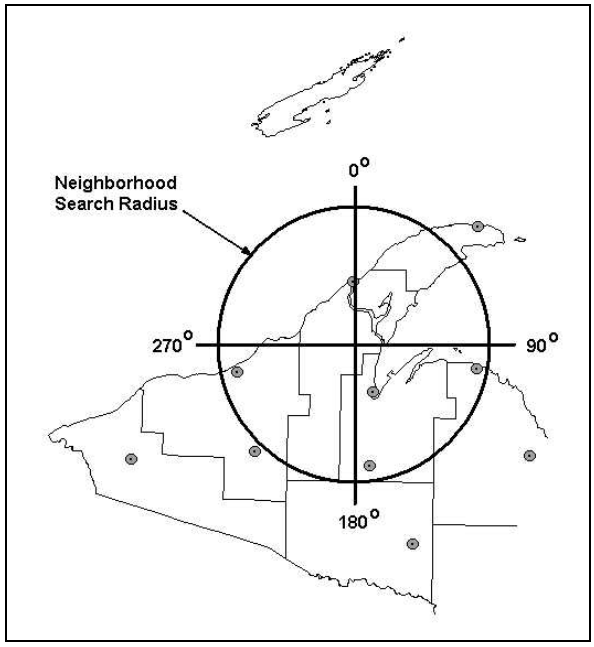

Figure E.3. Illustration of the neighborhood search radius assuming isotropic conditions.

However, the assumption of isotropic conditions is not realistic for many natural systems, so consideration of directional effects is recommended to model the spatial variation in the data.

If the semivariogram can be determined as stable, the presence of anisotropic conditions may be investigated to correct for any directional effects that may be present. Two directional categories of anisotropies exist, geometric and zonal anisotropy, that are defined by principal search direction, half-angles, and bandwidths. Figure E.4 illustrates the search method used in calculating the semivariance of an unsampled location (P1) while considering geometric anisotropies. Neighboring sample points are divided up by the lag cutoffs determined by the chosen lag distance. It should also be noticed that by selecting inappropriate half-angles and bandwidths, some sample points (*e.g.*, P3) may not be included in calculating the semivariogram. To avoid such situations, an appropriate number of search directions or large enough half-angles should be used to incorporate all sample points into the semivariogram. Zonal anisotropic effects are similar but are manifested in a third dimension.

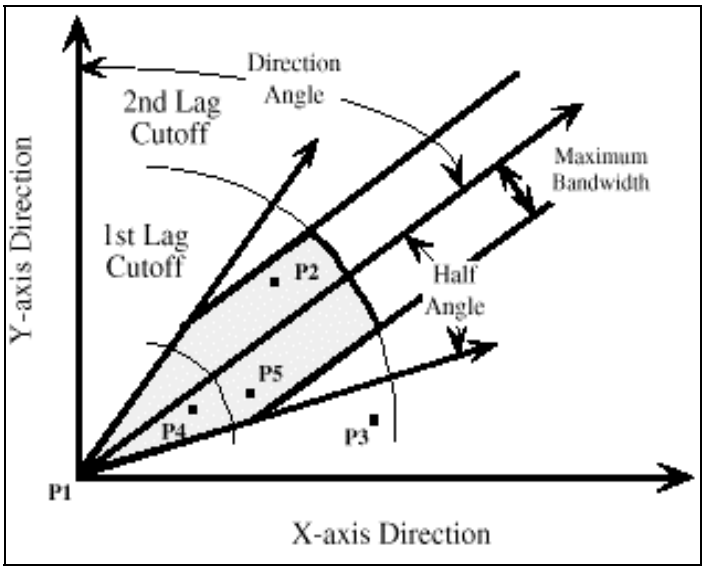

Figure E.4. Schematic of the search method used in calculating the semivariance of P1 with consideration of geometric anisotropies (Deutsch and Journel 1998).

If geometric anisotropy is present, the principal search directions, *i.e.* principal anisotropic axes, are identified by the direction of the experimental semivariogram possessing the greatest range. The minor anisotropic axis is usually located 90 degrees from the principal axis. Together, the principal and minor anisotropic axes define the shape of the neighborhood search window used in the kriging process, as shown in Figure E.5. It is recommended that the experimental semivariogram be calculated for at least four directions to verify that anisotropic conditions are present (Armstrong 1998).

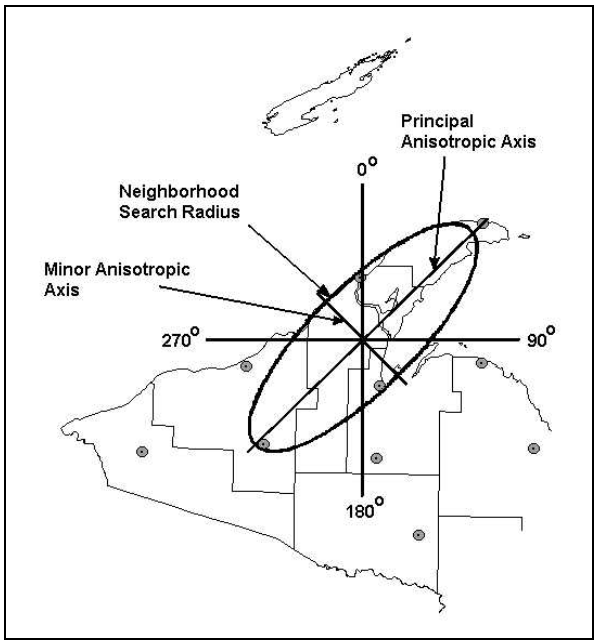

Figure E.5. Illustration of the neighborhood search radius with consideration of anisotropic effects.

After identifying a stable experimental semivariogram and correcting for anisotropic effects, the next step in the process involves fitting a suitable theoretical semivariogram model to the experimental semivariogram. Theoretical semivariogram models are mathematical functions, defined by parameters (*i.e.*, nugget, behavior at the origin, range of influence, sill, and anisotropies), that are used in identifying the size of the search neighborhood and assigning the weights in the kriging process. Some common theoretical models are the spherical, circular, exponential, Gaussian, and linear models (Armstrong 1998; Watson 1992). While fitting the model to the experimental semivariogram, the following criteria should be considered: 1) the model should minimize the residual error as in a goodness-of-fit test; and 2) semivariogram values based on greater number of points should be weighted more heavily.

E.1.3 The Estimation Process

As previously discussed, the theoretical semivariogram model is used during the kriging process to determine the appropriate interpolation weights. In ordinary kriging, the structural component, *i.e.* mean $m(x)$, of the regionalized variable is assumed unknown. An estimate at an unsampled point is given by (Burrough and McDonnell 1998):

$$\hat{z}(x_0) = \sum_{i=1}^{n} \lambda_i \cdot z(x_i) \tag{E.6}$$

where λ_i are the chosen weights, with $\sum_{i=1}^{n} \lambda_i = 1$ so that the estimate is unbiased; $\hat{z}(x_0)$ is the estimate; and $z(x_i)$ is a measurement at a sample point that is spatially correlated with the estimate at point x_0. The variance of estimation is given by (Burrough and McDonnell 1998):

$$\hat{\sigma}_e^2 = \sum_{i=1}^{n} \lambda_i \cdot \gamma(x_i, x_0) + \phi \tag{E.7}$$

where ϕ is a Lagrange multiplier associated with the unbiased constraint and $\gamma(x_i, x_0)$ is the semivariance of z between points x_i and the unsampled point x_0. For a detailed derivation of the ordinary kriging system, the reader is referred to the following references: Armstrong (1998), Clark (1987), Cressie (1991), Deutsch and Journel (1998), Journel and Huijbregts (1978), and Kitanidis (1993).

E.1.4 Spatial Averaging Through Block Kriging

Equation E.6 and Equation E.7 represent point kriging, which implies that all interpolated values relate to the area or volume of a sample, *i.e.* the support. For rainfall IDF estimates, the support is typically only a few inches in diameter (the area of a rain gage opening). Due to the high degree of short-range variation associated with these IDF

point estimates, ordinary point kriging may result in an interpolated surface possessing sharp spikes and pits (Burrough and McDonnell 1998). In terms of modeling the spatial behavior of IDF estimates, the presence of sharp spikes and pits within the interpolated surface is not reasonable.

Short-range variation between the interpolated point estimates may be smoothed using a method known as block kriging (Armstrong 1998). Block kriging provides a means of estimating an average value of the regionalized variable over a specified area. In an ordinary block kriging system, an average estimate $\hat{z}(x_B)$ at an unsampled block is given by (Burrough and McDonnell 1998):

$$\hat{z}(x_B) = \sum_{i=1}^{n} \lambda_i \cdot z(x_i) \tag{E.8}$$

with $\sum_{i=1}^{n} \lambda_i = 1$, as before. However, the minimum variance is now (Burrough and McDonnell 1998):

$$\hat{\sigma}^2 = \sum_{i=1}^{n} \lambda_i \cdot \bar{\gamma}(x_i, B) + \phi - \bar{\gamma}(B, B) \tag{E.9}$$

where $\bar{\gamma}(x_i, B)$ is the average semivariance between point x_i and the area *B*, as given by Equation E.10 (Burrough and McDonnell 1998) and illustrated in Figure E.6.

$$\bar{\gamma}(x_i, B) = \frac{1}{B} \cdot \int_B \gamma(x_i - x) dx \tag{E.10}$$

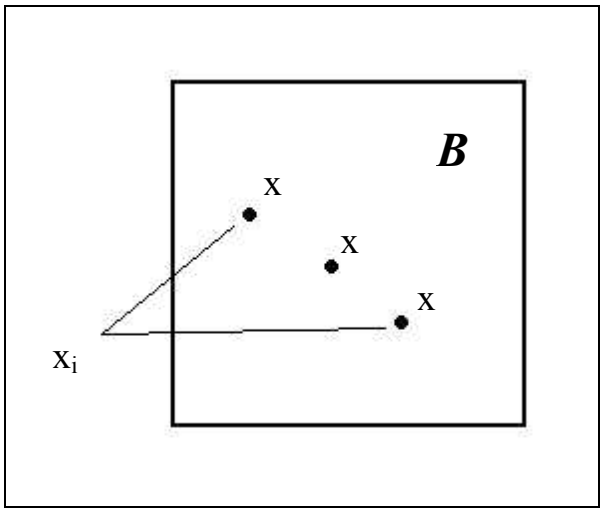

Figure E.6. Illustration of the process of averaging the semivariance between point x_i and all sampled points within area B (Armstrong 1998).

Similarly, $\bar{\gamma}(B,B)$ is the average semivariance between any two points x and x' located within area B, as given by Equation A.12 (Burrough and McDonnell 1998) and shown in Figure E.7.

$$\bar{\gamma}(B,B) = \frac{1}{B^2} \cdot \iint \gamma(x - x')dxdx' \tag{E.12}$$

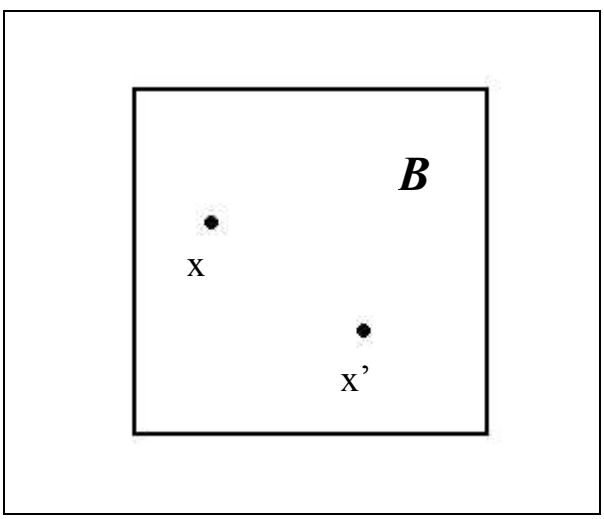

Figure E.7. Illustration of the process of averaging the semivariance between any two points x and x' located within area B (Armstrong 1998).

The estimation variance obtained using block kriging is inversely proportional to the block area (*B*) (Armstrong 1998; Burrough and McDonnell 1998). For a detailed derivation of the ordinary block kriging system, the reader is referred to Armstrong (1998), Clark (1987), Cressie (1991), Deutsch and Journel (1998), Journel and Huijbregts (1978), and Kitanidis (1993).

E.2 Results and Discussion

Preliminary rainfall IDF estimates in the form of isopluvial maps are presented and discussed. The isopluvial maps are generated by applying trend surface analysis, ordinary kriging, and universal kriging techniques to the spatial interpolation of a site-specific distribution parameter (the mean of the AMS data). In addition, comparisons between the preliminary rainfall IDF estimates and estimates presented by Huff and Angel (1992) and Sorrell and Hamilton (1990) are provided. For brevity, only isopluvial maps corresponding to the 2- and 100-year recurrence intervals and 1- and 24-hour durations are presented for comparison of results.

E.2.1 Trend Surface Analysis Results

As discussed in Section 6.3.1, trend surface analysis uses multiple regression to fit a polynomial surface to the entire set of sample observations, thereby generating an interpolated surface that models the broad regional trend in the data. The trend surface analysis results presented here were generated using UNCERT Version 1.20, a geostatistical uncertainty analysis package (Wingle 1995). Figure E.8 illustrates isopluvial maps of a) 2-year, 1- hour and b) 2-year, 24-hour rainfall intensities generated by fitting a third-order trend surface to the AMS data. Figure E.9 illustrates isopluvial

maps of a) 100-year, 1- hour and b) 100-year, 24-hour rainfall intensities generated by third-order trend surface analysis.

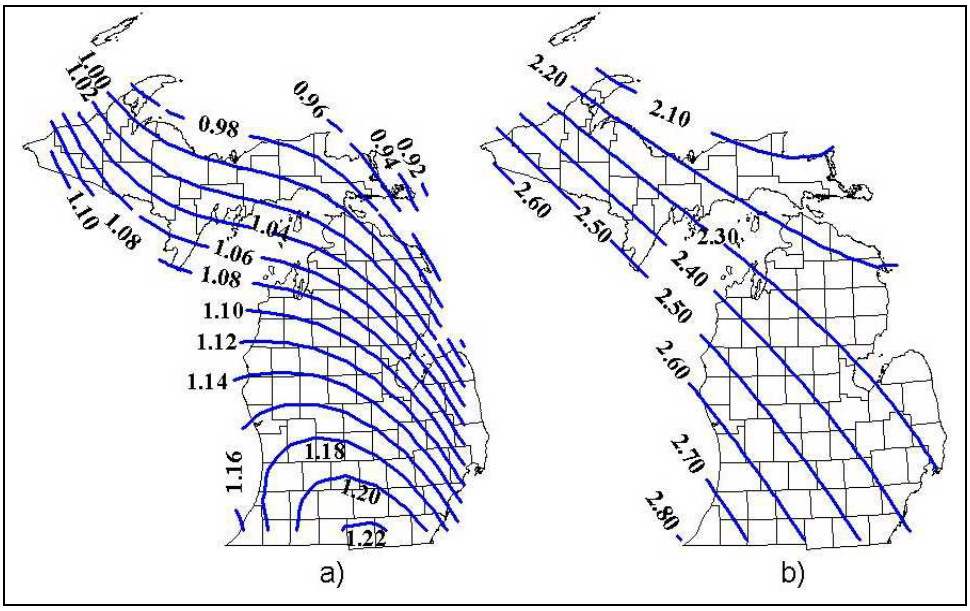

Figure E.8. Isopluvial maps of a) 2-year, 1- hour and b) 2-year, 24-hour rainfall intensities generated by applying a third-order trend surface to AMS data.

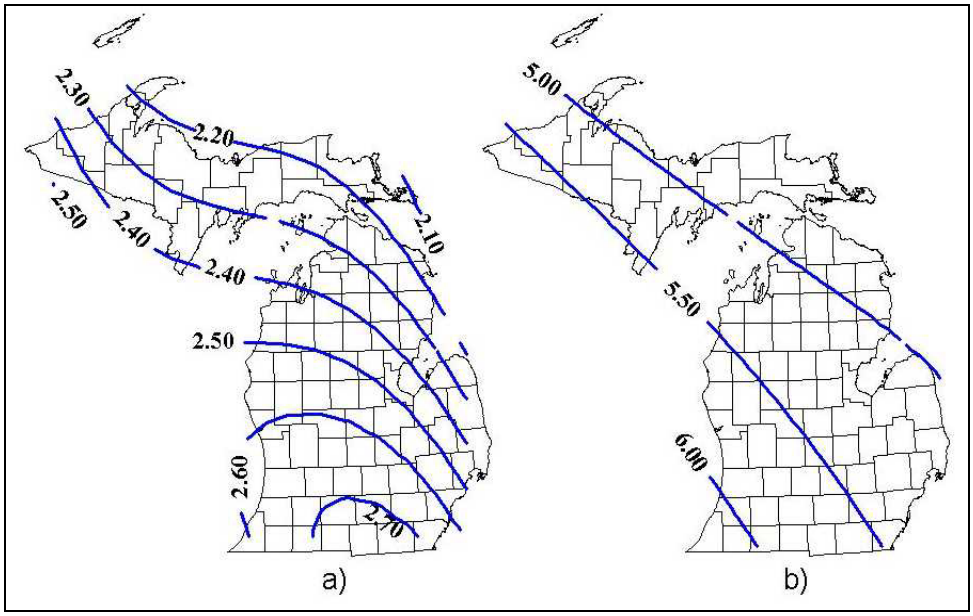

Figure E.9. Isopluvial maps of a) 100-year, 1- hour and b) 100-year, 24-hour rainfall intensities generated by applying a third-order trend surface to AMS data.

All isopluvial maps indicate similar patterns, with the highest rainfall intensities in the southwest part of the state and the lowest rainfall intensities in the northeast part of the state. These general isopluvial patterns are consistent with previous frequency analysis studies, as discussed later in this chapter.

Figure E.10 and Figure E.11 provide a visual comparison of trend surface analysis results applying a) third-order, b) fourth-order, and c) fifth-order polynomials to 1-hour and 24-hour AMS means, respectively. Table E.1 compares sample statistics of absolute residuals at observation sites between observed 1-hour and 24-hour AMS means and interpolated estimates generated by third-, fourth-, and fifth-order polynomials using trend surface analysis.

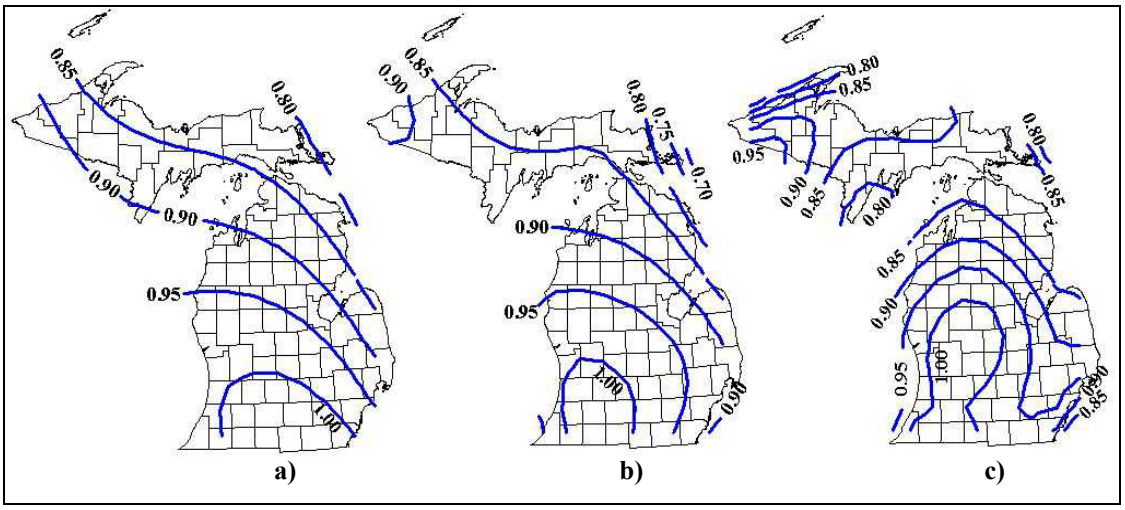

Figure E.10. Comparison of trend surface analysis results applying a) third-order, b) fourth-order, and c) fifth-order polynomials to 1-hour AMS means.

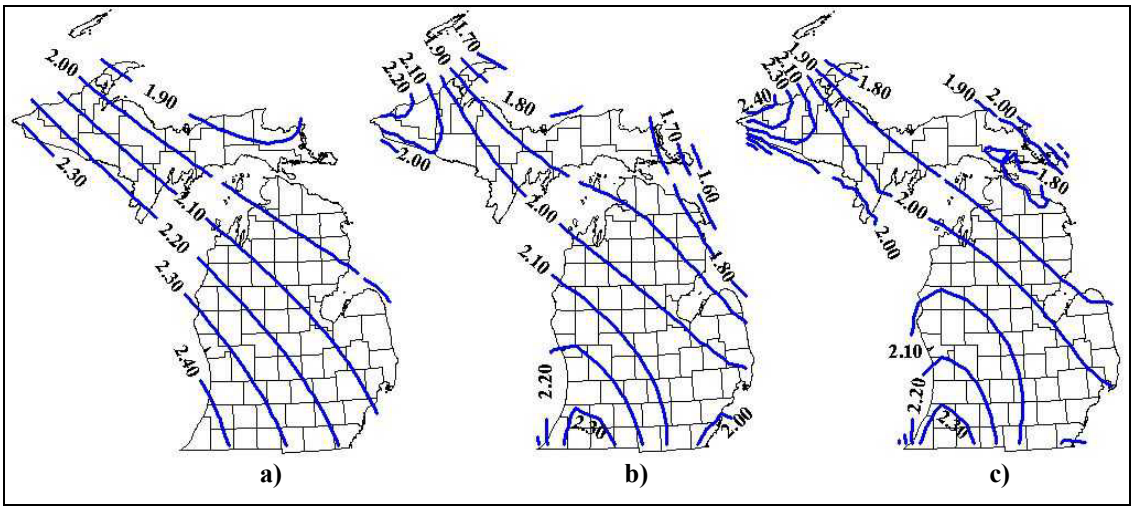

Figure E.11. Comparison of trend surface analysis results applying a) third-order, b) fourth-order, and c) fifth-order polynomials to 24-hour AMS means.

Table E.1. Sample statistics of absolute residuals at observation sites. Residuals are the differences between observed 1-hour and 24-hour AMS means and interpolated estimates generated by third-, fourth-, and fifth-order polynomials using trend surface analysis.

Duration	Sample Statistics	Trend Surface Analysis		
		3rd Order	4th Order	5th Order
1-hour	Maximum	0.221	0.221	0.208
	Minimum	0.002	0.000	0.003
	Mean	0.061	0.060	0.055
	Standard Deviation	0.050	0.050	0.048
24-hour	Maximum	0.282	0.258	0.249
	Minimum	0.000	0.000	0.000
	Mean	0.076	0.071	0.069
	Standard Deviation	0.063	0.056	0.054

With additional curvature, the higher order polynomials can be expected to provide a better fitting surface (Figure E.10 and Figure E.11). However, based on the sample statistics presented in E.1, fourth- and fifth-order trend surface analyses do not produce significantly better fits in comparison to the third-order trend surface analysis. Furthermore, artifacts of the higher order polynomials, known as edge effects, are unnatural looking isopluvial patterns along the state borders. Therefore, it would not be reasonable to place a high degree of confidence in results generated by fourth- or fifth-order trend surface analysis.

E.2.1 Ordinary Kriging Results

The process of geostatistical linear estimation involves two main steps: structural analysis and best linear unbiased estimation (BLUE). In general, structural analysis is the identification of a theoretical semivariogram model used to characterize the spatial variability in the variable of interest. BLUE uses the semivariogram model parameters to determine the interpolated estimates, which are unbiased and have a minimum variance.

Structural analysis and BLUE steps were performed using the ordinary kriging algorithm in UNCERT Version 1.20 (Wingle 1995) to generate the isopluvial maps. The structural analysis assumed isotropic conditions since consideration of anisotropic effects can only offer significant improvement in the kriging process if the uncertainty in the observed data is relatively low. Due to the high uncertainty typically associated with point rainfall IDF estimates, it was decided that investigating anisotropic effects would not likely provide a significant improvement in the IDF estimates.

In the structural analysis, the following criteria were considered in the selection and fitting of semivariogram models to the experimental semivariograms: 1) minimum variance (*i.e.*, goodness-of-fit) to experimental semivariogram and 2) number of sample pairs representing individual experimental semivariogram points. Figure E.12 illustrates the results of the structural analysis performed on 1-hour AMS means by fitting a spherical semivariogram model to the experimental semivariogram. Similarly, Figure E.13 illustrates the results of the structural analysis performed on 24-hour AMS means by fitting a Gaussian semivariogram model to the experimental semivariogram. At a lag distance greater than 2,000,000 feet (≈ 380 miles), as shown in Figure E.13, an abrupt linear rise in the experimental semivariogram occurs. Although the three furthermost experimental semivariogram points are based on only a few pairs of observations, the structural feature is indicative of a trend in the data. Appropriate treatment of the trend will be further investigated and discussed in the following section on universal kriging.

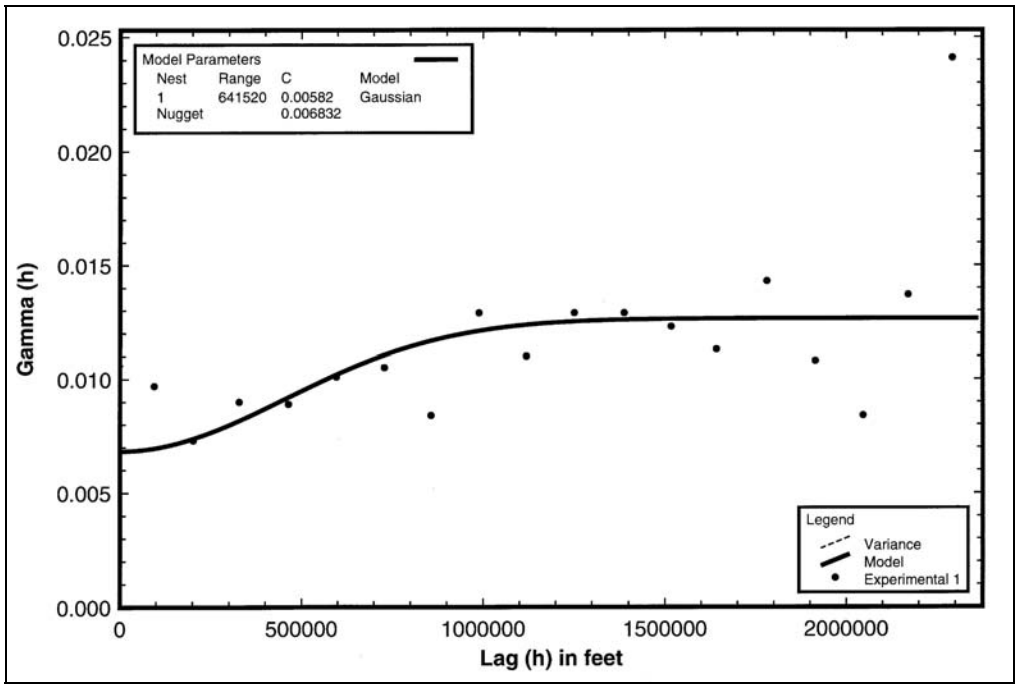

Figure E.12. Gaussian semivariogram model fitted to experimental semivariogram for 1-hour AMS means assuming isotropic conditions.

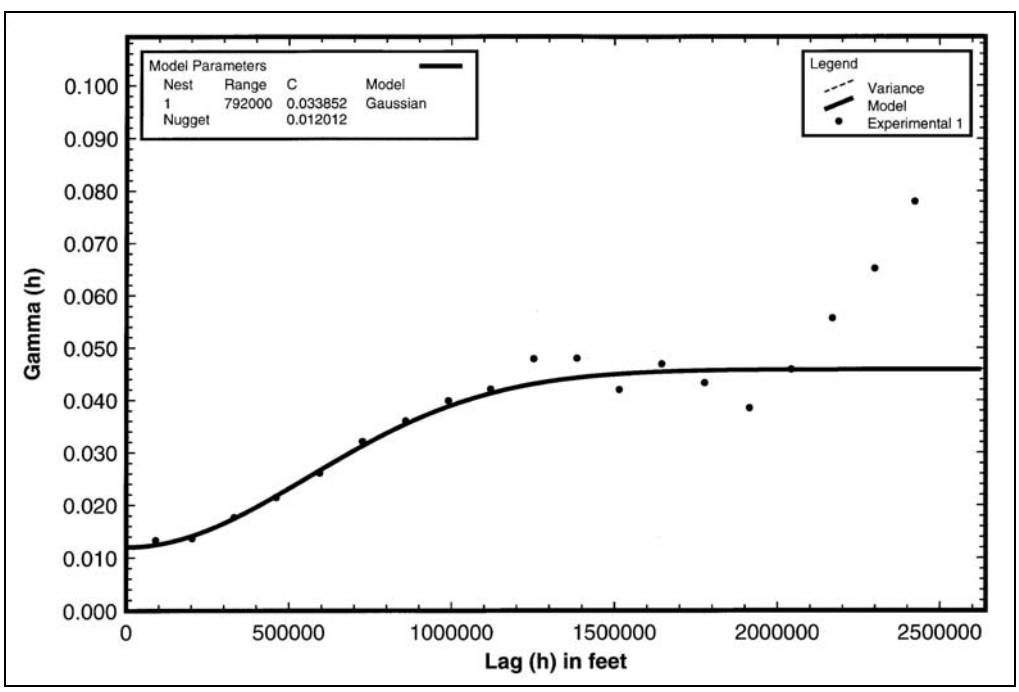

Figure E.13. Gaussian semivariogram model fitted to experimental semivariogram for 24-hour AMS means assuming isotropic conditions.

Model parameters defining the two Gaussian semivariogram models that were fitted to the AMS 1-hour and 24-hour means, respectively, are given in Table E.2. A lag distance of 132,000 feet (25 miles), equivalent to the average sample spacing, was selected and used in the structural analysis of all the data used in this study.

Table E.2. Model parameters defining the semivariogram models that were fitted to the AMS 1-hour and 24-hour means.

Control Parameters	**1-Hour Means**	**24-Hour Means**
Lag Distance (feet)	132,000	132,000
Model	Gaussian	Gaussian
Nugget (in^2)	0.0058	0.0120
Sill (in^2)	0.0068	0.0339
Range of Influence (feet)	641,520	792,000

Ordinary kriging results are illustrated in Figure E.14 and Figure E.15. Figure E.14 illustrates isopluvial maps of a) 2-year, 1- hour and b) 2-year, 24-hour rainfall intensities, and Figure E.15 illustrates isopluvial maps of a) 100-year, 1- hour and b) 100-year, 24-hour rainfall intensities. In both cases, results are based on AMS data.

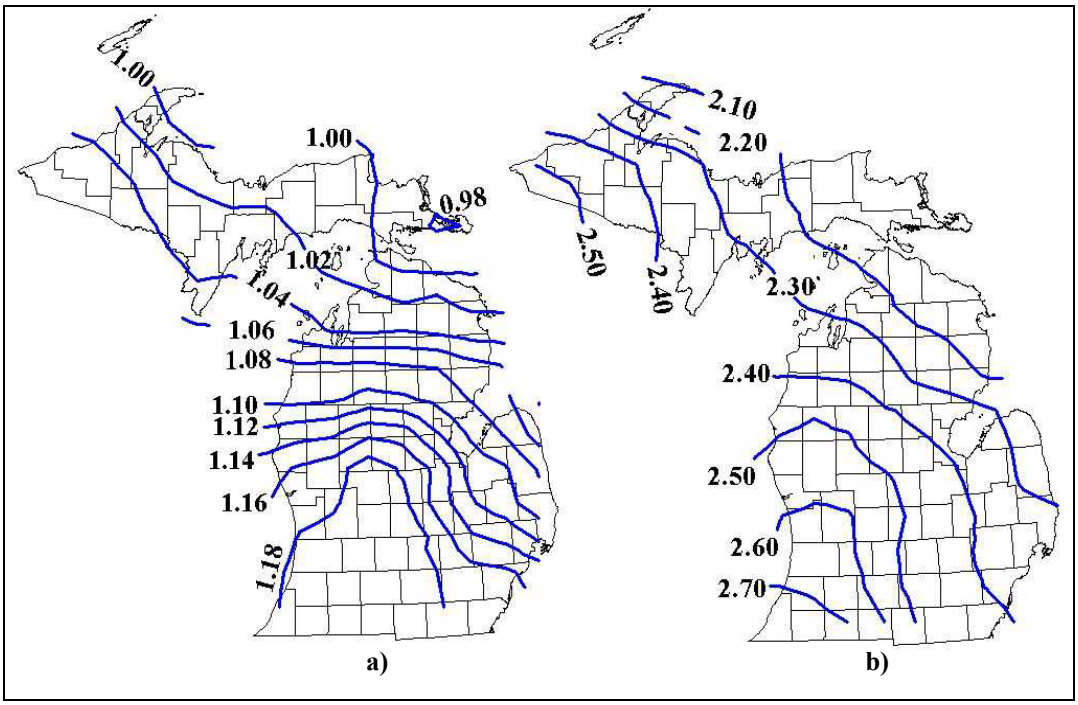

Figure E.14. Isopluvial maps of a) 2-year, 1- hour and b) 2-year, 24-hour rainfall intensities generated by ordinary kriging on AMS data.

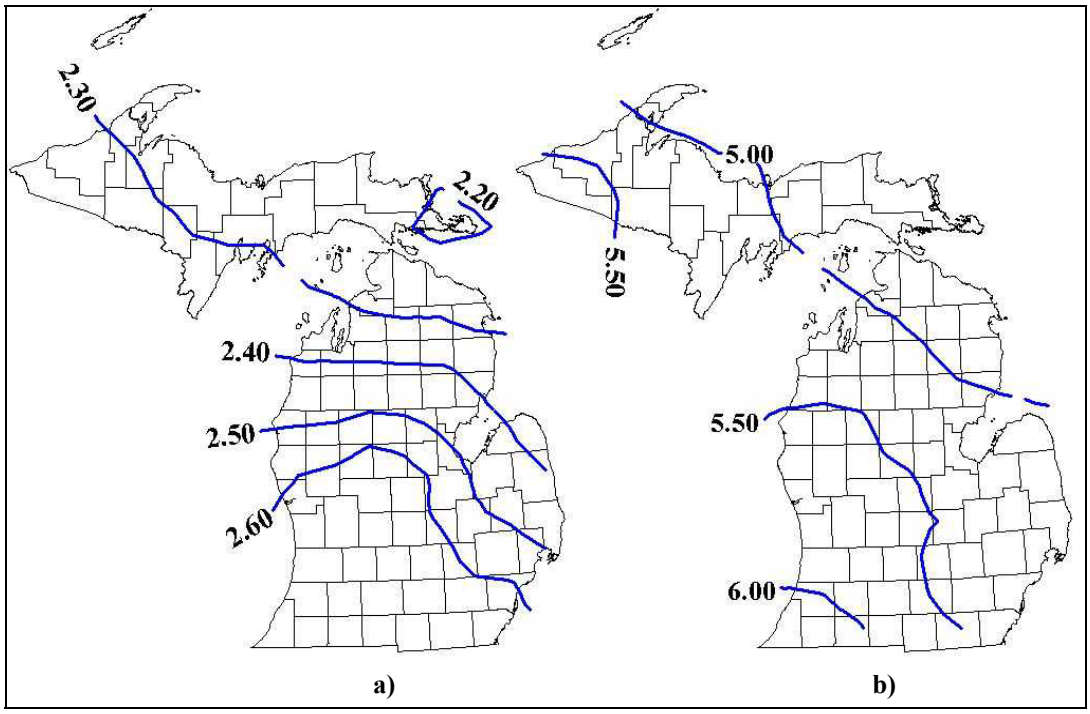

Figure E.15. Isopluvial maps of a) 100-year, 1- hour and b) 100-year, 24-hour rainfall intensities generated by ordinary kriging on AMS data.

E.2.3 Universal Kriging Results

In practice, universal kriging is used when a known trend exists in the data. The process of universal kriging combines the theories of both trend surface analysis and ordinary kriging. Trend surface analysis is first performed on the data to remove the existing trend. Ordinary kriging is then performed on the residuals of the trend surface. As a final step, the trend is added back into the ordinary kriging result performed on the residuals.

Figure E.16 and Figure E.17 illustrate the experimental semivariograms of the residuals from the 1-hour and 24-hour AMS means, respectively. For each experimental semivariogram, no theoretical semivariogram model was suitable due to the phenomenon known as a pure nugget effect. Identification of a pure nugget effect can be made when the experimental semivariogram appears relatively flat (Journel and Huijbregts 1978). Recall from Section 6.3.1, the nugget represents the discontinuity at the origin of the semivariogram signifying the data is highly variable at distances shorter than the sample spacing (Armstrong 1998). A pure nugget represents the absence of a spatial structure, or spatial independence between the samples, thereby corresponding to "white noise" that can not be corrected for at the current or larger sample spacing (Journel and Huijbregts 1978). Therefore, in this study, universal kriging appears to be incapable of improving the IDF estimates provided by trend surface analysis or ordinary kriging.

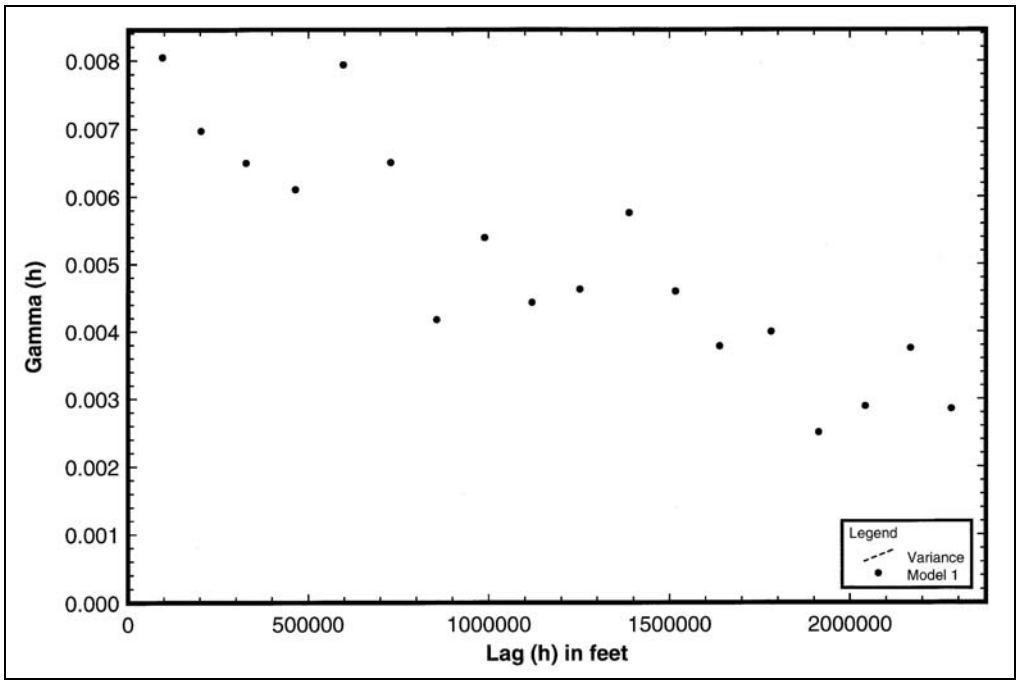

Figure E.16. Experimental semivariogram of the AMS 1-hour residuals.

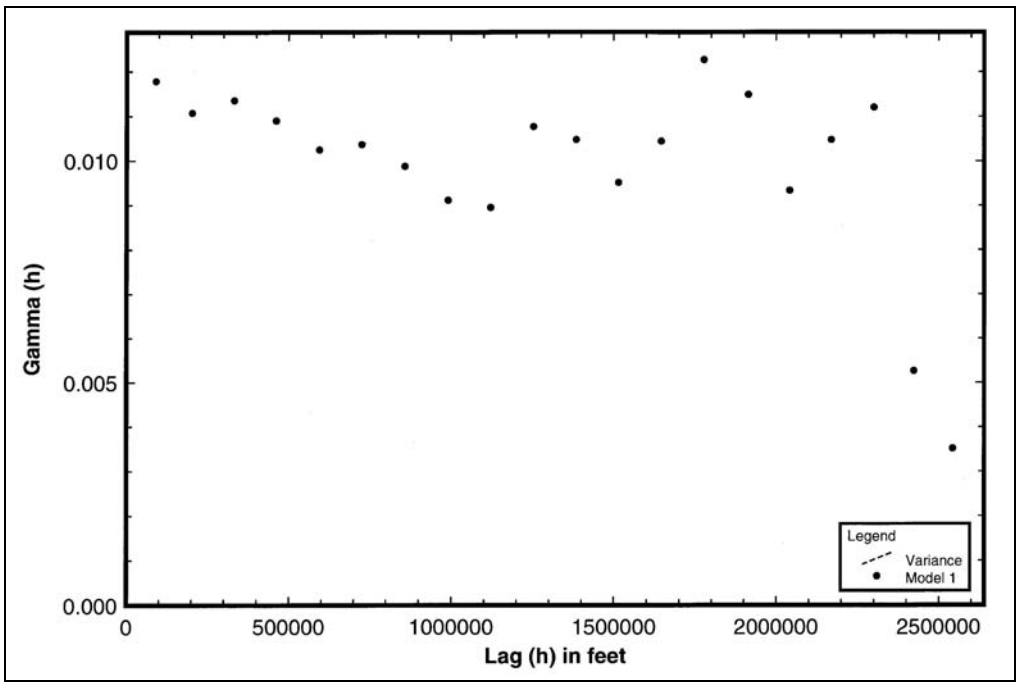

Figure E.17. Experimental semivariogram of the AMS 24-hour residuals.

Appendix F Interactive GIS Model

Though not fully tested and implemented, a prototype GIS model was developed to query and display site-specific IDF curves based on the updated point IDF estimates and regional frequency analysis results. This appendix outlines the tools used to develop the interactive GIS model and instructions for using the model to obtain site-specific IDF curves.

F.1 Tools Used in Development of Model

ArcView GIS Version 3.1, developed by Environmental Systems Research Institute, Inc., was selected for this study due to package's built in script language (i.e., Avenue) and customization functionality. In addition, ArcView GIS was chosen for its common usage in the industry. The final product is a customized ArcView GIS project file, called mdotidf.apr, which is compatible on both UNIX and PC platforms. The project file contains four scripts written in Avenue script language. A brief description of the functionality of the four scripts is presented in Table F.1 Proper execution of the model is dependent on the existence of two GIS coverages, Counties and idf_grid. The Counties coverage is a line coverage of Michigan's county boundary lines and is used only for visual orientation to select the site of interest. The idf_grid is the GIS grid coverage with attribute table populated with the updated IDF estimates of six recurrence intervals (0.5, 0.2, 0.1, 0.04, 0.02, 0.01 per year) and the seven durations (1, 2, 3, 6, 12, 18, and 24 hours).

Table F.1. Description of functionality of Avenue scripts.

Avenue Script	Functionality
1	Sets up model by verifying location and name of necessary GIS coverages.
2	Loads all necessary GIS coverages into existing or new view document.
3	Creates and activates tool button that provides the user with "point-and-click" capability in selecting a specific geographic location.
4	Queries grid attribute table for IDF estimates representative of selected location; Plots and displays a set of IDF curves in layout document.

F.2 Querying and Displaying Site-Specific IDF Estimates

This section outlines step by step instructions for querying and displaying site-specific IDF estimates within the *mdotidf.apr* project file. However, it is assumed that the user possesses basic knowledge of ArcView GIS and prior experience opening and saving project files.

F.2.1 Step 1: Orientation to Interface and Initial Setup

Assuming the mdotidf.apr project file is currently open, the four scripts, which make up the interactive GIS model, have been linked to a pulldown menu, called MDOT-IDF, located on the right-hand side of the view document menu bar, as shown in Figure F.1 (Note: The view document menu bar cannot be seen unless a view document is currently active.)

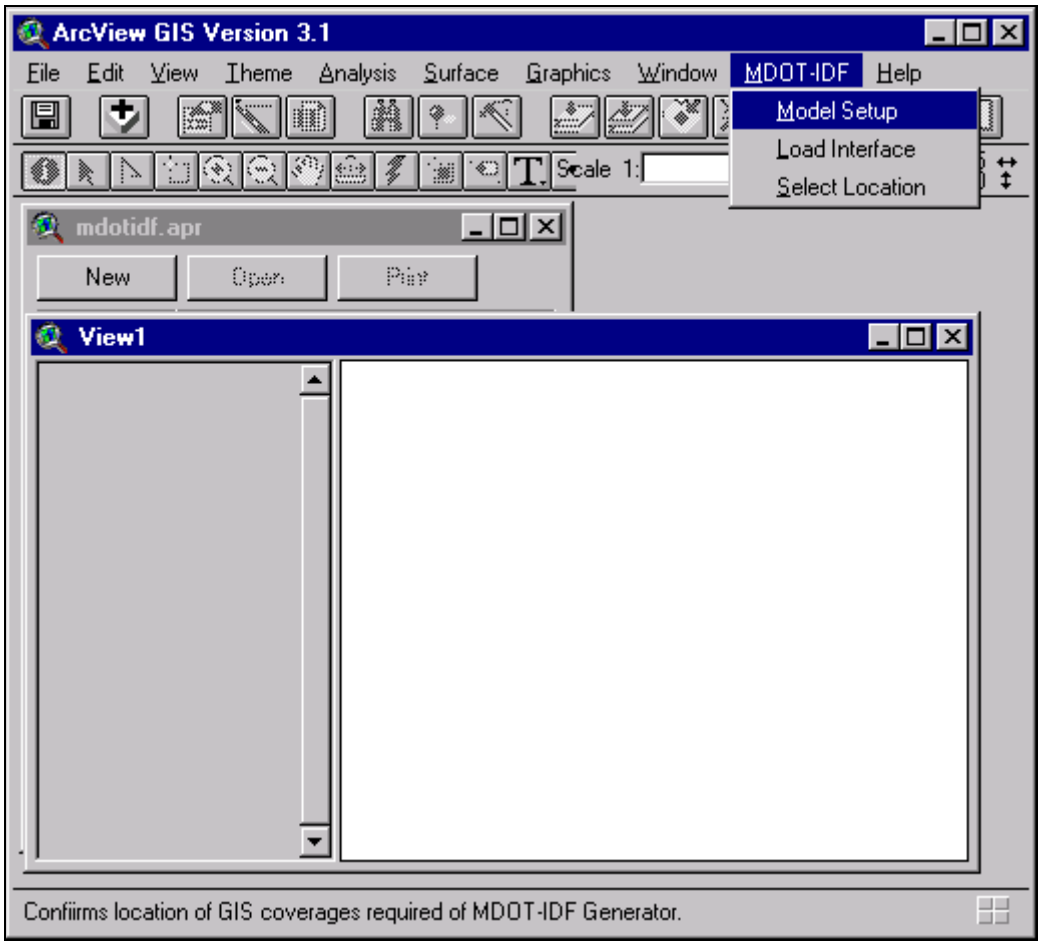

Figure F.1 Location of *MDOT-IDF* menu pulldown.

The first step in querying and displaying site-specific IDF estimates is to ensure that a view document, called "Select Location", does not currently exist in the project's table of contents (TOC). If "Select Location" does not exist, open and make active a new view document and continue to Step 2. If "Select Location" view does exist, open, make active, and verify that the *Counties* and *idf_grid* coverages exist within the "Select Location" view. If the two coverages have been loaded, leave "Select Location" active and continue to Step 2.

F.2.2 Step 2: Model Setup

With the view document active, set up the model by selecting Model Setup located on the MDOT-IDF pulldown menu. After selection, a popup window will appear, as shown in Figure F.1, requesting verification of the names and locations of the two GIS coverages necessary for execution of the model. Default names for the two counties are Counties and idf_grid. If a work directory was specified in ArcView GIS prior to setting up the interactive GIS model, the default location for the two coverages will be the work directory. Otherwise, the two locations will be blank. The user should click OK after verifying that the names and locations are correct. After verification, a second popup window will appear to instruct the user to Step 3 or Step 4, if "Select Location" and the two GIS coverages already exist.

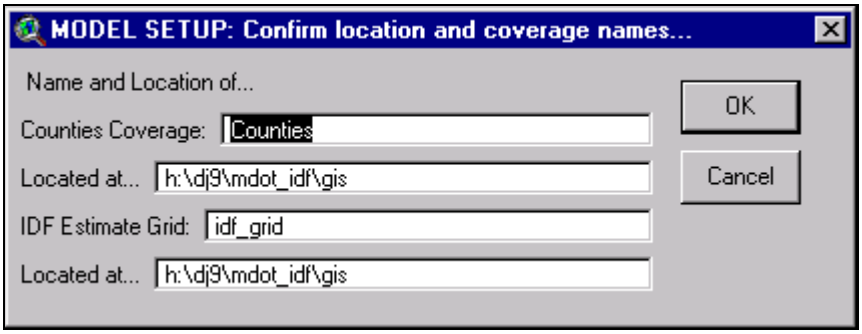

Figure F.1. MODEL SETUP window requesting verification of names and locations of the two necessary GIS coverages for execution of interactive GIS model.

F.2.3 Step 3: Load Interface

By selecting Load Interface located on the MDOT-IDF pulldown menu, the two GIS coverages are added to the active view. (Note: This process may take approximately one minute.) A popup window will appear, instructing the user to proceed to Step 4. By

clicking OK, the popup window will disappear as the "Select Location" view is maximized to display the county boundaries of Michigan, as shown in Figure F.3.

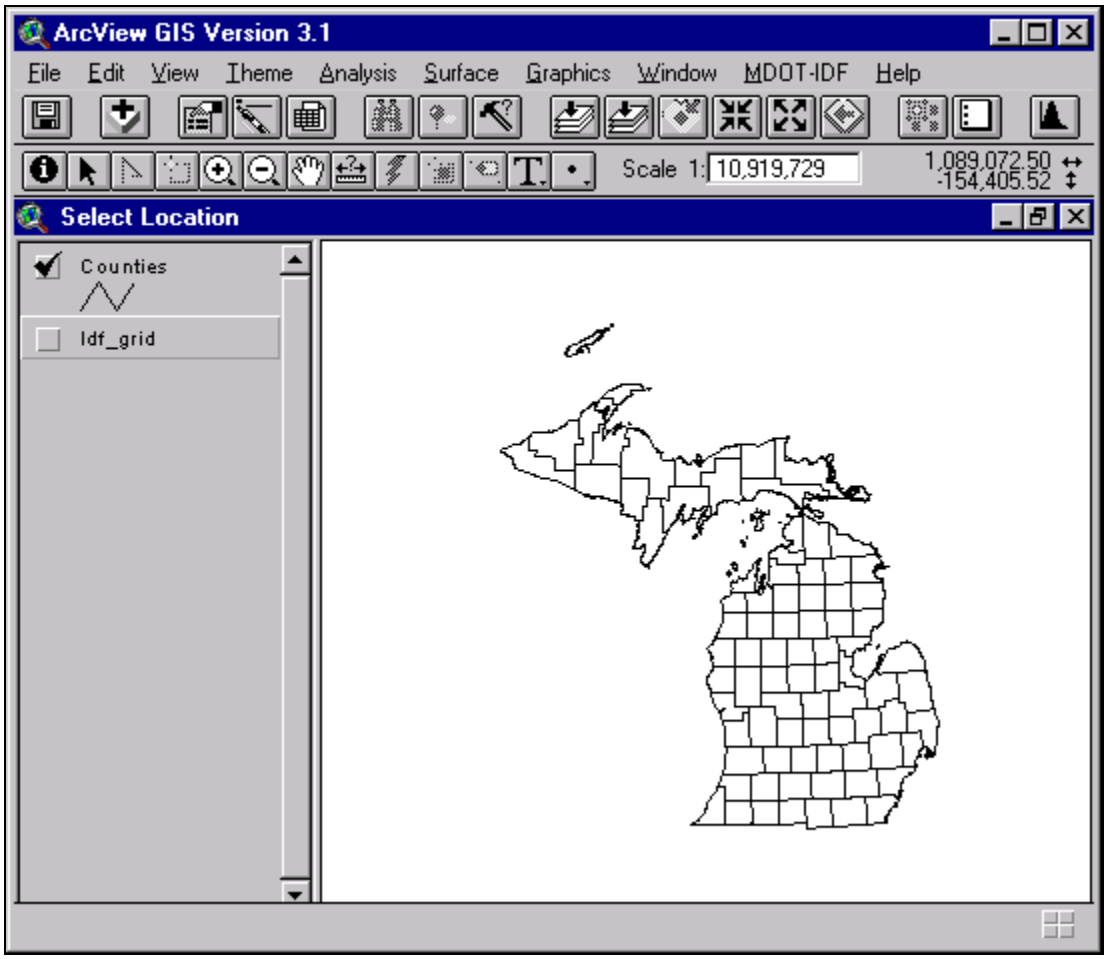

Figure F.2. Appearance of interactive GIS interface after execution of Step 3.

F.2.4. Step 4: Select Location

By selecting Selection Location on the MDOT-IDF pulldown menu, the user now has "point-and-click" capabilities for querying and displaying site-specific IDF estimates. By moving the mouse to the geographical area of interest within the Michigan's boundary and clicking once, a popup window, as shown in Figure F.4, will appear providing the user with the option to name the selected area.

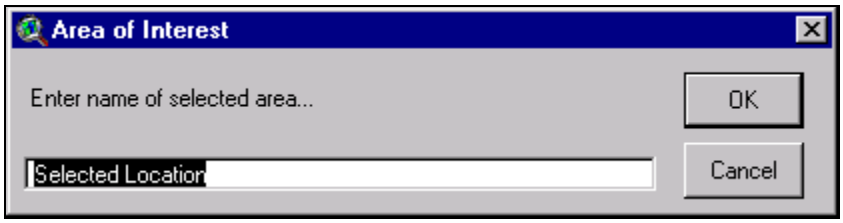

Figure F.3. Popup window providing option to input name of selected area.

The model will then query the attribute table of the grid coverage and plot the IDF estimates in a layout document in the form of IDF curves, as shown in Figure F.5. (Note: This process may take approximately one minute.)

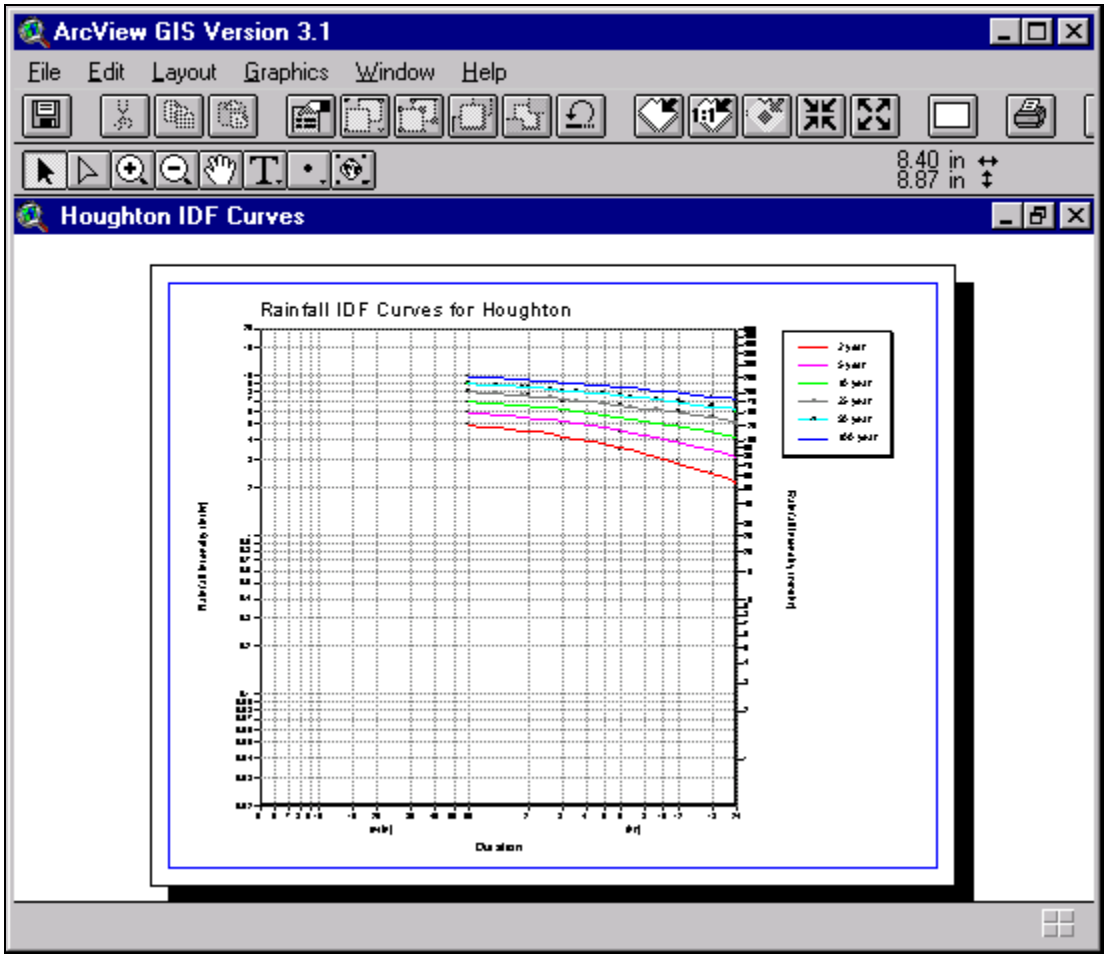

Figure F.4. Plotted IDF curves for selected area generated by the interactive GIS model.

Appendix G Scale Invariance of Short Duration Data

G.1 Introduction

Since hourly precipitation data were much more widely available than short duration (< 1 hour) data, a method was applied in which hourly precipitation data were related to short duration data by assuming time scale invariance. This chapter explores the validity of this assumption and recommends further research to develop reliable short-duration IDF estimates.

In recent years, the study of phenomena with scale fluctuations has grown from applications in physics phenomena such as statistical theories of turbulence and in quantum field theory (Gupta and Waymire, 1990) to hydrologic phenomena such as stochastic rain model application and intensity-duration-frequency (IDF) curve formulation. While empirical equations have been used for nearly one hundred years to explain the form of IDF curves, scale invariance has helped to understand these relationships at a higher level. Sherman (1905) first developed a generalized IDF relationship, and many other versions of this relationship have been developed in the years since. All forms of the generalized IDF relationships assume that rainfall depth or intensity is inversely related to the duration of a storm raised to a power, or scale factor. A sampling of these studies will be reviewed.

Wenzel (1982) reported a generalized IDF relationship that expressed graphical information from an IDF curve in mathematical form. This empirical equation was stated as:

$$i = \frac{A}{(t+b)^n}, \qquad \text{(G.1)}$$

where i is the intensity in inches per hour, A is a constant for a given return period, b and n are constants independent of return period, and t is the duration in minutes. The constants in this equation have been found to vary with location, and also should not be applied beyond the range of intensity and duration for which they were developed. Wenzel found that n varied from 0.40 to 0.84 around the nation for a ten-year return period, with a value of 0.81 in Chicago. Wenzel concluded that n is very variable across the nation depending on location.

Recently, this IDF relationship has been updated by Koutsoyiannis et al. (1998). In this paper, a more consistent formulation of the IDF relationship was determined by using a general formula for the relationship in which the specific forms are rigorously derived from the underlying probability distribution function of the maximum intensities. The general IDF relationship was determined to be

$$i = \frac{a(T)}{b(d)}, \tag{G.2}$$

where i is the intensity, T is the return period, and d is the duration of the storm. The variable $a(T)$ is determined from the probability distribution function of the maximum intensity, and

$$b(d) = (d + \theta)^{\eta}, \tag{G.3}$$

where θ and η are parameters to be estimated ($\theta > 0$, $0 < \eta < 1$).

Applying this general relationship to data in Greece and noting the variation on the parameters allowed Koutsoyiannis et al. to study the geographical variation of IDF curves. The data were used from 13 recording stations uniformly distributed in a 25,000-km^2 area in Greece (1/5 the total area of Greece) where five major rivers are located. It was determined that the η parameter could not be estimated accurately without the use of

short-duration (hourly) data. Also, the θ parameter could not be estimated accurately, but it was determined that equating it to zero would be adequate. The geographical variation of the η parameter was found to be very slight, and that more specifically, η can be considered constant in each of the homogeneous subregions in this study area. The parameters used to solve for *a(T)* do vary geographically. In conclusion, it was determined that the proposed IDF relationship is an efficient parameterization and good basis for the regionalization of the IDF relationship.

Although many previous studies depend on curve-fitting techniques, studies applying scaling hypotheses to rainfall statistics have become popular over the past 20 years. These studies include Lovejoy and Schertzer (1985), Gupta and Waymire (1990), Burlando and Rosso (1996), Menabde, Seed, and Pegram (1999), and Naghettini (2000).

Lovejoy and Schertzer (1985) showed that the atmosphere follows a symmetry principle – termed generalized scale invariance - in which the statistical properties of the small and large scale are related to each other by a magnification coupled with a differential stratification from gravity and differential rotation from the Coriolis force. This was shown through the use of two models, one that modeled the rainfall field using a hierarchy of simple pulses, and a second that showed the scaling of the pulses. Lovejoy and Schertzer concluded that this scale invariance principle and the models used to illustrate it might become useful in future hydrologic studies, as they capture the extreme variability of rain over a wide variety of scales in a very simple way.

Gupta and Waymire (1990) analyzed spatially averaged rainfall rates and river flows to determine the nature of deviations from simple scaling. Simple scaling was defined physically as a mathematical property in which probability distributions remain

invariant with respect to scaling by a function λ^{θ}, where $\lambda > 0$ is the spatial scale parameter and θ is a characteristic exponent. In order to obtain empirical results, continuous rainfall data was used from GATE (Global Atmosphere Research Program, Atlantic Tropical Experiment). The first six statistical moments of the rainfall data were calculated. These were the moments, $E\left[Y_{\lambda}^{h}\right]$, that corresponded to each λ value. In order to examine the scaling properties, a conditional moment, m_h, was expressed as:

$$\log m_h(\lambda) = a_h + \theta_h \log \lambda \quad , \qquad \text{(G.4)}$$

where a_h is the intercept, and θ_h is the slope. This conditional moment, $m_h(\lambda)$, was then plotted versus λ on a log-log plot. The intercept (a_h) and slope (θ_h) were found by regression. From the graph, it was seen that there was a log-log linearity of the data. But as $h \rightarrow h\theta$, the plot becomes nonlinear. Also θ_h was less than zero for all h analyzed. This violates the assumption of linearity and of simple scaling in the wide and strict sense. Therefore, simple scaling was not applicable, but the results of this paper show that if multiscaling is used, hydrologic fluxes of continuous rainfall and river flow data can be scaled down, similar to statistical theories of turbulence.

These results were taken one-step further by Burlando and Rosso (1996) as they derived a method to create a general distribution-free framework to model extreme storm probabilities from the scaling properties of observed rainfall data. A distribution-free framework is then derived to model IDF curves based on either simple scaling or multi-scaling assumptions. The simple scaling and multiscaling properties were applied to data at two stations in Italy. In summary, Burlando and Rosso (1996) determined that both the simple scaling and multiscaling log-normal models can be used to predict the growth curve of rainfall depth in a design storm as a function of storm duration. Although some

of the observed data displayed simple scaling, multiscaling provides a more general conceptual framework. Yet if a model follows simple scaling, the increase in model performance will be small if multiscaling is used, and a lot more complex as multiscaling involves many more parameters.

Building on the previous scaling work, Menabde et al. (1999) developed a simple scaling methodology to use daily rainfall statistics to infer the IDF characteristics for short-duration rainfall (less than one day). The scaling hypothesis was verified by fitting the model to two different sets of data. The first data set was recorded in Melbourne, Australia, representing the mid-Atlantic temperature climate with rainfall throughout the year. The second data set was recorded in Warmbaths, South Africa representing a warm, semi-arid climate with summer rainfall consisting mainly of convective storms. In brief, this paper showed that the scaling hypothesis worked for two different rain gages in two different climates. Menabde et al. (1999) also concluded that estimates of the scaling coefficient (or scale factor), η, can be made using a shorter record of high-resolution rain gages in the same climatic region. Once the scaling coefficient has been established for a gage or set of gages in a region, short-duration IDF estimates can be obtained from the analysis of daily data.

Similar to Menabde et al. (1999), Naghettini's (2000) purpose was to derive an IDF relationship for short duration rainfall from the statistical characteristics of daily data using simple scaling relationships. Naghettini used the scaling hypothesis developed by Menabde et al. (1999) to determine the scaling coefficient for the recording rainfall gaging station of Vespasiano, located in Belo Horizonte, Brazil. It was determined that the scaling coefficient for this station was equal to 0.69. IDF curves were deduced using

this coefficient and compared to curves derived from actual data. These curves matched almost exactly. The scale factor, η, was also estimated for data observed at the Papagaios, Lagoa do Gouvea, and Entre Rios de Minas stations located in the metropolitan region of Belo Horizonte. Although there is a great distance between these stations, and they have very different elevations and annual average rainfall depths, the simple scaling hypothesis has been verified at these gages for durations greater than 45-minutes, with η varying from 0.75 to 0.81. High values of the scaling factor show both that the short duration data are more variable with respect to daily data and that the intensity of the short-duration storms is relatively high.

G.2 Application of Scale Invariance Methodology to Data in Michigan

The assumption of scale-invariance was used to extrapolate short-duration IDF results for Detroit to locations throughout the state. Specifically, given the estimate of *n*-minute rainfall intensity for a given return period in the Detroit area, an estimate of *n*-minute rainfall intensity for the same return period at another location was estimated as:

$$I_x^n = I_D^n \left(\frac{I_x^{60}}{I_D^{60}} \right) , \qquad \text{(G.5)}$$

where

I_x^n = *n*-minute rainfall intensity at site *x*

I_D^n = Average *n*-minute rainfall intensity in the Detroit area

I_x^{60} = 60-minute rainfall intensity at site *x*

I_D^{60} = Average 60-minute rainfall intensity in the Detroit area

The major assumption in this extrapolation method is that scaling relationships are the same throughout the state, i.e., that there is one scaling factor that can be applied to the entire state. In order to confirm this, the scale-invariance property was evaluated in greater detail. Multiscaling is most often used in rainfall analysis, as it has been shown that simple scaling does not work for continuous rainfall (Gupta and Waymire, 1990). Recently, however, Menabde et al. (1999) have shown that simple scaling holds for annual maximum series (AMS) of rainfall intensity. The verification method used by Menabde et al. (1999) and Naghettini (2000) was used to verify the scaling assumption applied in this study.

Simple scaling in the "strict sense" is defined as an equality of distributions by Menabde et al. (1999):

$$u_n \overset{dist}{=} \left(\frac{n}{\square}\right)^{-\eta} u_{\square} \qquad \text{(G.6)}$$

where

u_n = random variable with duration, n,

$u_{¥}$ = random variable with duration, ¥ ,

η = scaling coefficient,

$\left(\frac{n}{\square}\right)^{-\eta}$ = scale ratio,

and $\square > n$.

For the purposes of this study, this property was rewritten as:

$$\frac{I_x^n}{I_x^{60}} = \left(\frac{n}{60}\right)^{-\eta} = \frac{I_D^n}{I_D^{60}} \qquad \text{(G.7)}$$

Equation G.6 was rewritten as equation G.7, as the intensities in equation G.7 are quantiles from the GPA distribution used in this study. Therefore, the intensities in equation G.7 are equal in distribution, as in equation G.6. Thus, by equation G.7, it is assumed that the scaling coefficient in the Detroit area for durations less than 60 minutes is the same as the scaling factor at any other location in the state for durations less than 60 minutes.

The data in Detroit area were analyzed to ensure that it did indeed conform to simple scaling. Annual exceedence series (AES) data for two different stations, with complete records from 5-minute to 24-hour durations, were analyzed. From equation G.7, simple scaling in the wide sense can be expressed as (Menabde et al. 1999):

$$\left\langle I_d^q \right\rangle = f(q) d^{-\eta q} \tag{G.8}$$

where $f(q)$ is some function of q (the qth moment), $\left\langle I_d^q \right\rangle$ is the qth moment of the intensity data (mm/hr), d is the duration (hours), and η is the scalar. In Figures G.1 and G.2, the qth moment of the intensity is plotted against the duration on a log-log scale for the Howell station and the Detroit City Airport station, both located in the Detroit Metropolitan area. In order to remain consistent with Menabde et. al (1999), moments from q = 0.5 to 3 were plotted.

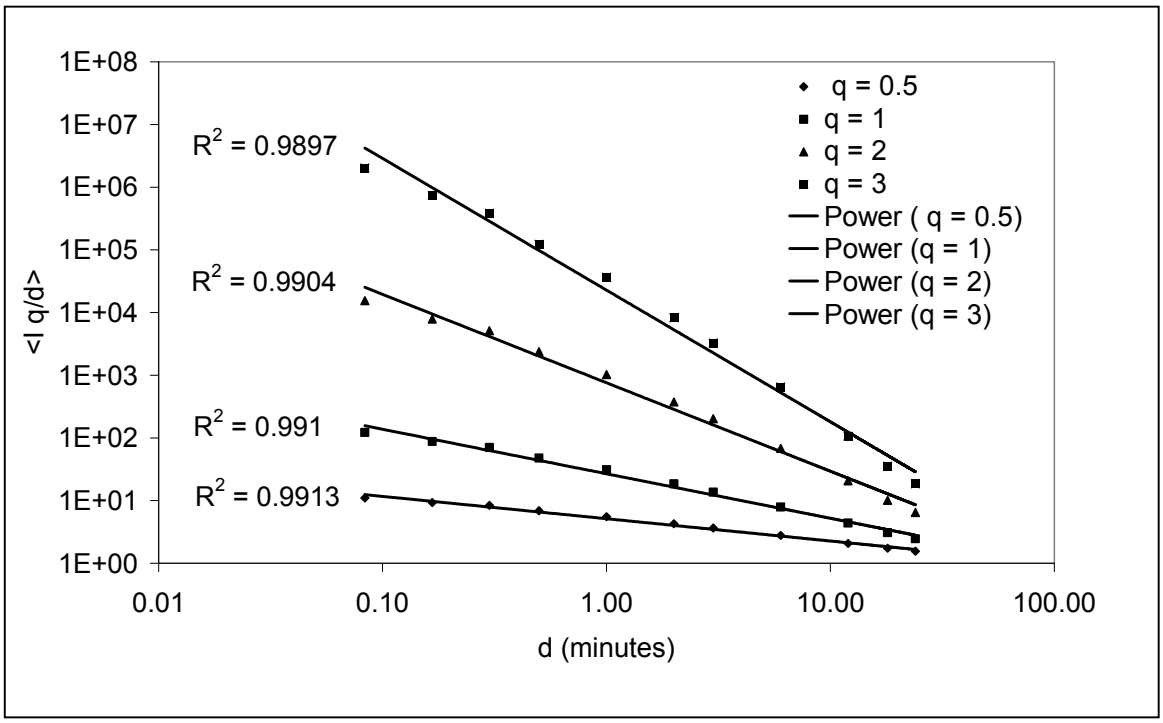

Figure G.1. Scaled moments of AES data versus duration for the Howell station located in the Detroit Metropolitan area.

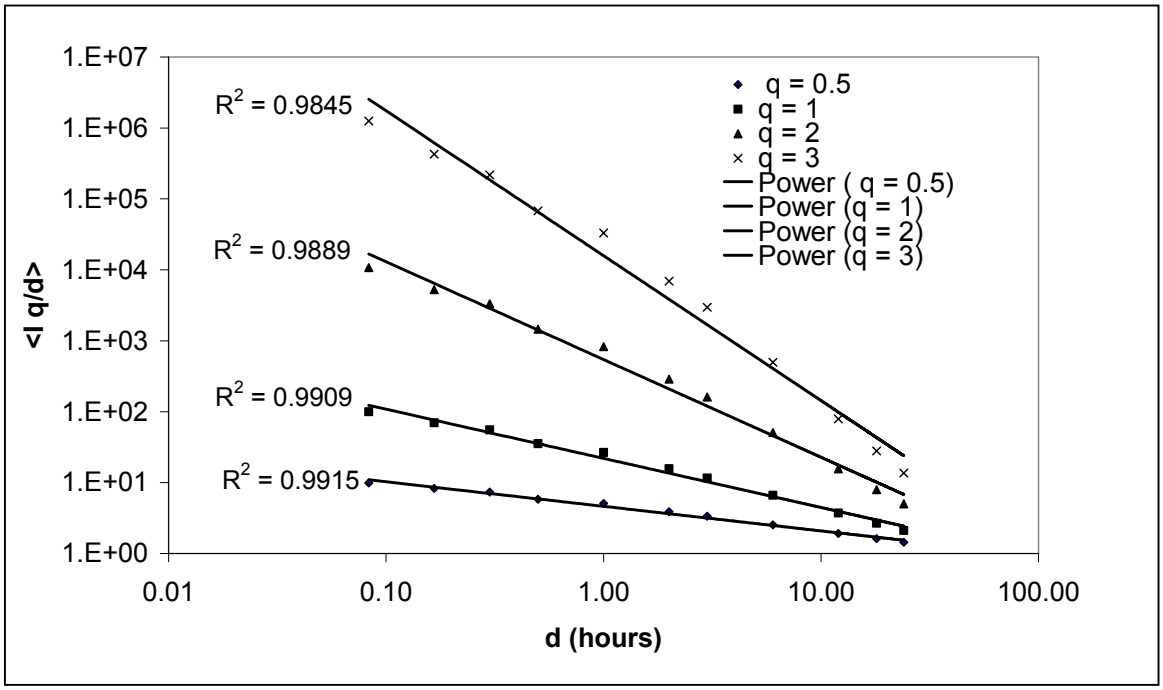

Figure G.2. Scaled moments of AES data versus duration for the Detroit City Airport station located in the Detroit Metropolitan area.

It can be seen from Figures G.1 and G.2 that the data are linearly related, and there is not a break at duration of 60 minutes between the short- and long-duration data. As both gages show a similar scaling relationship, it is possible that scaling may be applicable in the Detroit area. From these plots, it was determined that there was a well-defined scaling relationship for durations greater than or equal to ten minutes, but could not be verified for less than ten minutes. In order to determine if the data follow simple scaling or multi-scaling, the scaling exponent, $-\eta q$, was plotted versus the moment, q, as can be seen in Figure G.3. Once again the data were linearly related, with an R^2 values of 0.9999 for the Howell station and 0.9993 for the Detroit City Airport station. Therefore, simple scaling can be assumed in this situation. If the data had not been linear, then this would have been a case of multi-scaling. The slope of this line is the scale factor, η, which is 0.68 for the Howell station and 0.65 for the Detroit City Airport station. These scale factors are quite close.

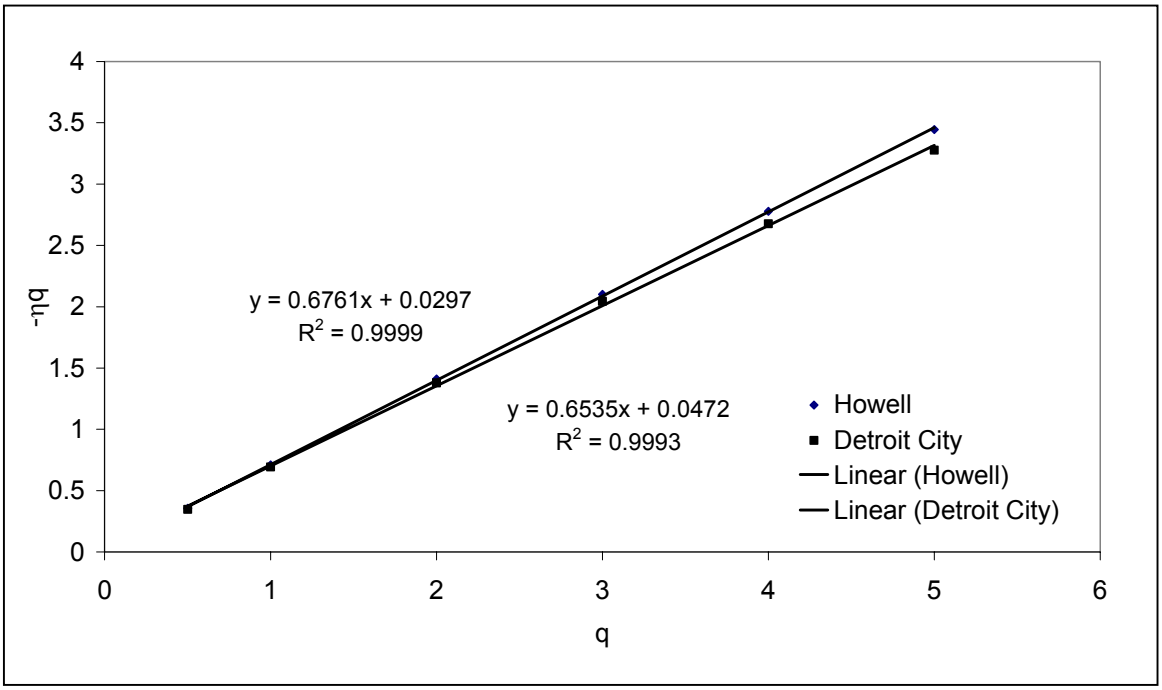

Figure G.3. The slope of the line provides an estimate of the scaling factor for the Howell station and the Detroit City Airport station in the Detroit Metropolitan area.

After verification of scaling of IDF estimates in the Detroit area, the assumption of scaling was examined at a representative sample of stations throughout the state. The only data readily available for less than the 1-hour duration for stations not in the Detroit area are 15-minute continuous data from the National Oceanic and Atmospheric Administration. An AMS data set was derived from the continuous data, and the first four moments were calculated for durations of 15 minutes up to 24 hours. As with the Detroit data, these moments were plotted against duration on a log-log scale to determine whether scaling could be assumed.

Figures G.4 and G.5 show the scaling of the moments for the Gladwin station in the central Lower Peninsula (L.P.) of Michigan and the Bruce Crossing station in the northwest Upper Peninsula (U.P.) of Michigan, respectively. The linearity of the moments seen here is similar to the other 22 stations that were examined, indicating that

for durations greater than 15 minutes, scaling appears to be applicable throughout Michigan. As shown in Figure G.6, the scaling exponent, -ηq, was plotted versus the moment, q, to determine if simple scaling is applicable and to estimate the scale factor for stations throughout the state.

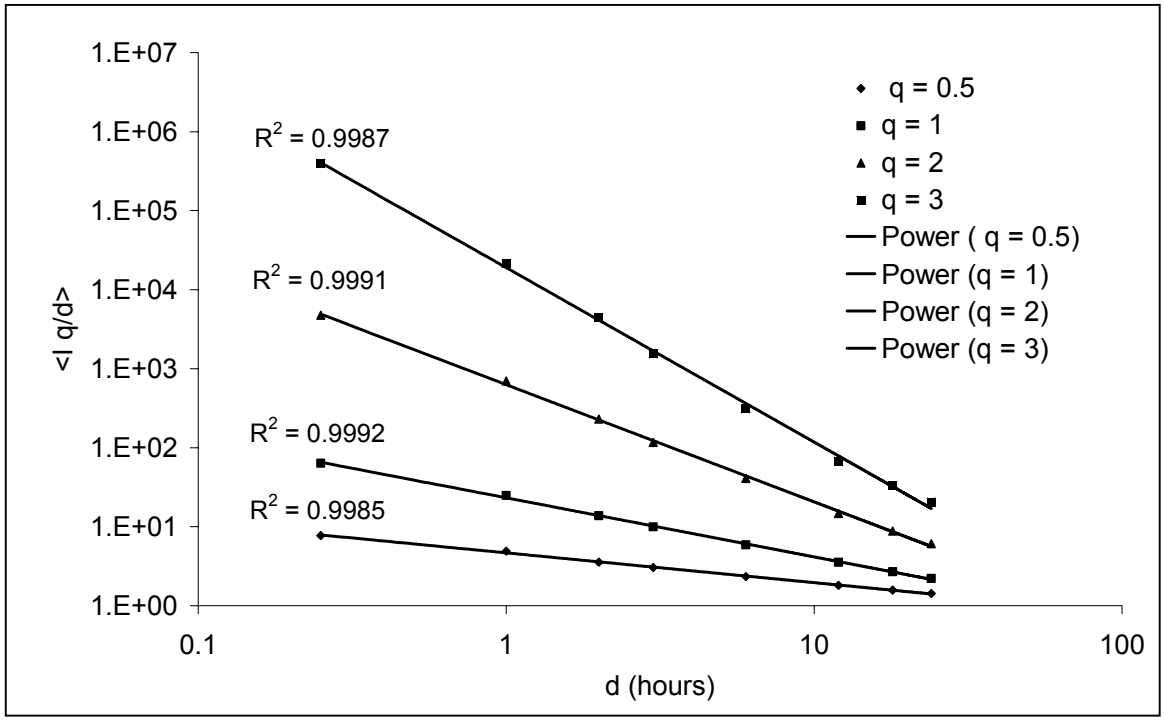

Figure G.4. Scaled moments of AMS data versus duration for the Gladwin station located in the central Lower Peninsula of Michigan.

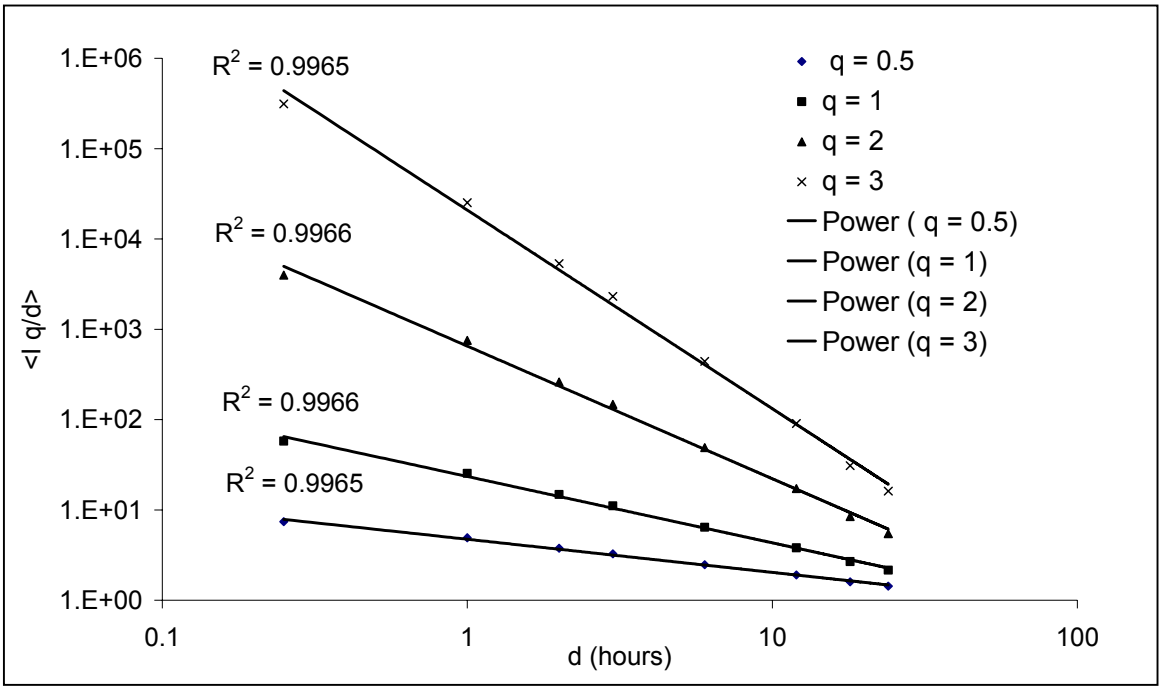

Figure G.5. Scaled moments of AMS data versus duration for the Bruce Crossing station located in the northwest Upper Peninsula of Michigan.

In Figure G.6, the scaling coefficients, or the slopes of the line, is 0.72 for the Gladwin station, with a R^2 value of 0.9999, and 0.73 for the Bruce Crossing station with a R^2 value of 1.0000 (The lines plot on top of one another). This indicates that simple scaling could be applied at these two stations instead of the more complicated multiscaling.

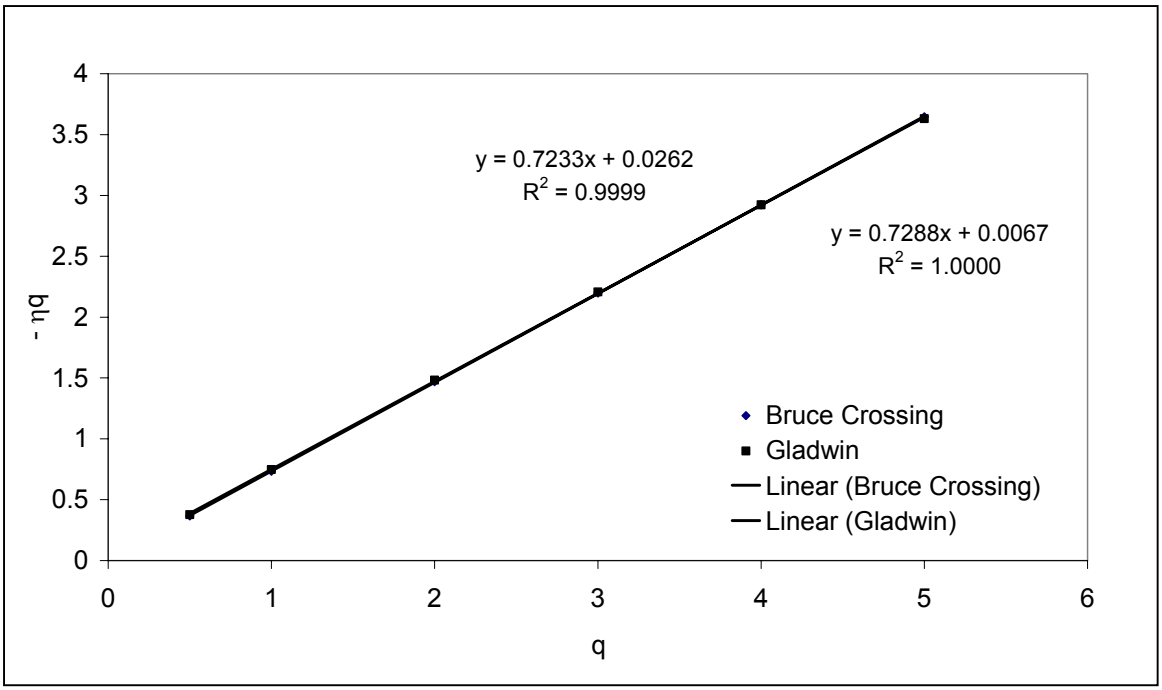

Figure G.6. Linear relationship indicates simple scaling applicable at Bruce Crossing station in the northwest Upper Peninsula of Michigan and the Gladwin station in the central Lower Peninsula of Michigan.

The scaling coefficients of 0.72 and 0.73 found in Figure G.6 were typical for the 24 stations examined, with an average scalar equal to 0.72 and a standard deviation of 0.044. However, a few stations had significantly lower scalar exponents (as low as 0.62). These stations were generally located on the western part of the Lower Peninsula, close to or on Lake Michigan, as seen in Figure G.7, indicating that the effect of the lake should be studied further. It can also be seen in Figure G.7 that the scaling coefficients were generally higher in the northeastern part of the state.

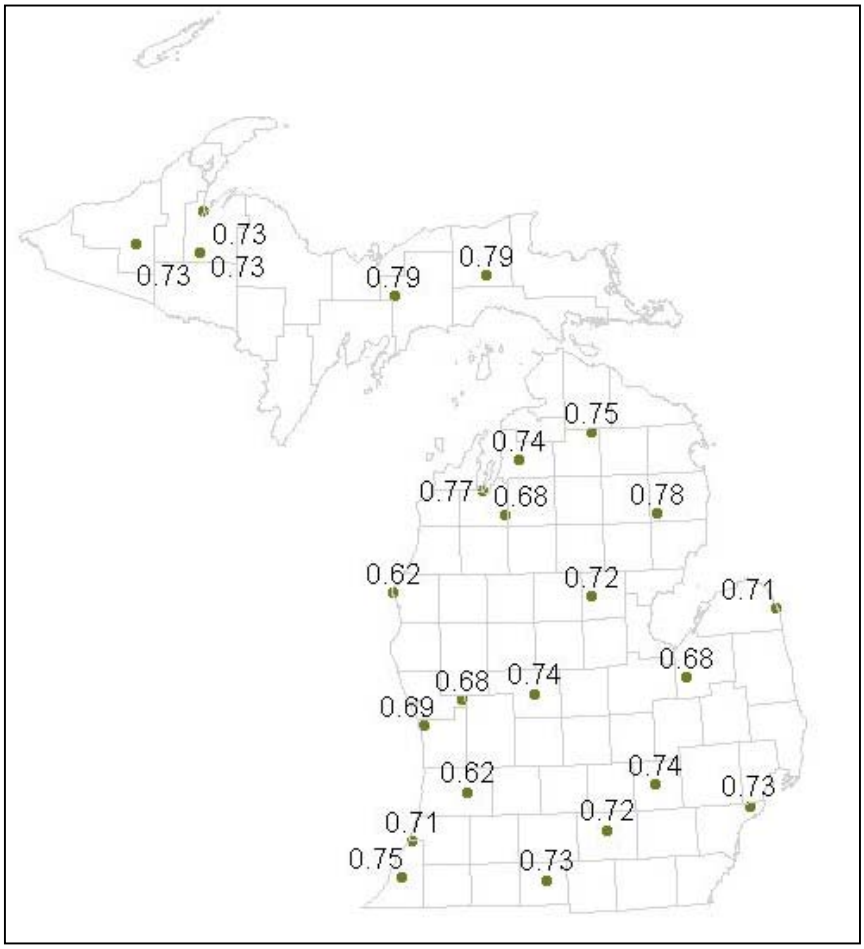

Figure G.7. Scaling coefficients of 24 stations located around the state.

Upon analysis of revised IDF estimates for Michigan, it appears that the assumption of simple scaling is reasonable for the purpose of deriving short-duration IDF estimates. Using this assumption, the average scalar around the state using durations of fifteen minutes and greater is 0.72.

G.3 Comparison with Previous Rainfall Frequency Studies

In previous IDF studies for Michigan, ratios and interpolation equations were used to determine short-duration rainfall intensities. For instance, to derive IDF estimates for durations shorter than 30 minutes in *TP-40*, Hershfield (1961) used empirical factors that were developed from analysis of short-duration rainfall values at different stations

around the country. These empirical ratios and the corresponding ratios developed for comparison in this study are given in Table G.1. The ratios are very similar, with the new ratios being the same as or slightly greater than the old. There may be several reasons for these differences. First, Hershfield's study included estimates for the entire United States, and this study included estimates only for the State of Michigan. Also, nearly forty years of additional data were used to calculate the new ratios. Sampling variability in both studies may also have made a difference.

Table G.1. Comparison between the average relationship between 30-minute rainfall and rainfall for other durations for the same return period.

Duration (min)	TP-40 Ratio	New Ratio
5	0.37	0.39
10	0.57	0.59
15	0.72	0.72
60	1.27	1.43

In NOAA Technical *Memorandum NWS Hydro-35* (*Hydro-35*), Frederick et al. (1977) found that the average ratios from *TP-40* worked in many parts of the country, but they have a geographic pattern and vary with return period. Although this study utilized short duration data (data for durations from 5 to 60 minutes were obtained from recording rain gages at approximately 200 NWS stations), an empirical equation was developed to obtain isopluvial maps for the 10- and 30- minute durations:

$$R_n = C_n(R_{m2}) + (1 - C_n)(R_{ml}) \tag{G.9}$$

where R_n is the required frequency value for N minutes, R_{m1} and R_{m2} are mapped values for a lesser and longer duration, and C_n is the interpolation constant. The equations that were adopted to obtain these values are as follows:

$$\text{10-min value} = 0.59(\text{15-min value}) + 0.41(\text{5-min value}) \quad \text{(G.10)}$$

$$\text{30-min value} = 0.49(\text{60-min value}) + 0.51(\text{15-min value}) \quad \text{(G.11)}$$

In order to interpolate short duration values for areas with only hourly recording stations, the 2-year 60-minute map was created first and used as a guide to obtain shorter durations.

In order to compare the new IDF estimates to those from *Hydro-35*, equations G.10 and G.11 were applied to the new IDF estimates. For the 10-minute estimates, the difference between the interpolation and scaling methods ranged from 0.50% to 3.01%. For the 30-minute estimates, the difference between the interpolation and scaling methods ranged from 3.44% to 11.49%. Although the percent difference for the 10-minute estimates decreased with increasing return period, the percent difference for the 30-minute estimates increased with increasing return period. As the *Hydro-35* equations apply to the entire Eastern and Central United States, it is possible that the coefficients do not take the geographical differences into account effectively. Also, about twenty years of data has become available since these interpolation equations were developed. While these differences are not too great, they have serious design implications in some cases.

Although the results presented in this chapter are interesting and useful, more research needs to be done. More specifically, research needs to be done to study lake effects on the scaling coefficient, and scale invariance of short-duration IDF estimates for neighboring

Midwest states should be examined. More short duration precipitation recording stations are also needed in Michigan to obtain more accurate IDF estimates. Short-duration data from durations of five minutes and greater may be located at some station locations in Michigan, but in paper rather than electronic form. If this data becomes available in electronic form, it would be advisable to perform a scaling analysis with this new data to determine more conclusively if simple scaling is applicable for short durations.