REGIONAL ANALYSIS OF ANNUAL PRECIPITATION MAXIMA IN MONTANA

By Charles Parrett

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Multiply	By	To obtain
foot	0.3048	meter
inch	25.4	millimeter
mile	1.609	kilometer
square mile	2.59	square kilometer
hour	3,600	second
minute	60	second

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Regional Analysis of Annual Precipitation Maxima in Montana

By Charles Parrett

Abstract

Dimensionless precipitation-frequency curves for estimating precipitation depths having large recurrence intervals were developed for 2-, 6-, and 24-hour storm durations for three homogeneous regions in Montana. Within each homogeneous region, at-site annual precipitation maxima were made dimensionless by dividing by the at-site mean and pooled for analysis to yield a single dimensionless frequency curve applicable for each duration. *L*-moment statistics were used to help define the homogeneous regions and to develop the dimensionless precipitation-frequency curves.

Data from 405 daily and hourly precipitation stations operated by the National Weather Service and 54 daily precipitation stations operated by the Natural Resources Conservation Service were used to develop the database of annual precipitation maxima. Statistical tests were applied to the annual precipitation maxima to ensure that the data were not serially correlated and were stationary over the general period of data collection (1900-92). The data also were tested for spatial independence using the interstation correlation coefficient and found to have a small degree of interstation correlation.

Several attempts were made to delineate homogeneous regions. Three regions previously delineated on the basis of physiography and climate were tested and found to be acceptably homogeneous for purposes of this study. The same regional boundaries were used for all storm durations. Region 1 consisted of generally mountainous western Montana where large storms generally receive their moisture from the Pacific Ocean. Region 2 included the mountains forming the eastern edge of the Rocky Mountain range where large storms are often the result of the orographic uplifting of moisture systems originating in the Gulf of Mexico. Region 3 consisted of the plains areas of eastern Montana where large storms may originate from moisture sources in the Pacific Ocean or the Gulf of Mexico.

Within each homogeneous region, regional values of *L*-moments and *L*-moment ratios were used to calculate parameters of several candidate probability distributions. A goodness-of-fit test was used to help select an acceptable distribution for each duration within each region. The distribution that most often satisfied the goodness-of-fit test and was thus selected as the best distribution for all durations and regions was the 3-parameter Generalized Extreme Value (GEV) distribution. The GEV distribution was used to construct dimensionless frequency curves of annual precipitation maxima for each duration within each region. Because each region exhibited some heterogeneity and because of uncertainty about the appropriate probability distribution, each dimensionless frequency curve was considered to be reliable for recurrence intervals up to the effective record length rather than the station-years of record. Because of significant, though small, interstation correlation in all regions for all durations, the effective record length was considered to be less than the total number of station-years of data. The effective record length for each duration in each region was estimated using a graphical method and found to range from 500 years for 6-hour duration data in Region 2 to 5,100 years for 24-hour duration data in Region 3.

Use of the dimensionless frequency curves to estimate precipitation depths for specified durations and exceedance probabilities at ungaged sites requires the estimation of mean at-site values of annual storm depth for the specified durations. Ordinary least-squares regression equations for the estimation of mean storm depths for durations of 2, 6, and 24 hours were developed. Explanatory variables for the regression equations included site location (latitude and longitude) and mean annual precipitation. The regression equations were tested against methods for estimating mean values previously developed by the National Weather Service and were determined to be generally more reliable within Montana than the previously developed methods. Use of a nearby precipitation station to estimate mean storm depth at an ungaged site was also tested and found to be at least as reliable as use of a regression equation.

INTRODUCTION

Because the consequences of dam failure can be catastrophic, spillway design typically is based on the magnitude of an extremely rare, large flood. For those dams, where the risk to human life would be large in the event of failure, spillways are commonly designed to safely pass the Probable Maximum Flood (PMF). The PMF is an extreme flood that is considered to be the largest that could occur at a given site considering the most adverse combination of prevailing meteorologic and hydrologic conditions. The determination of the PMF for a given site is a fairly complex procedure that requires use of a rainfall-runoff model to simulate the runoff from a storm having the Probable Maximum Precipitation (PMP) depth under "worst-case" antecedent-moisture and infiltration conditions. Determination of the PMP storm, in turn, is also complex and is based on the extrapolation of data from the largest storms known to have occurred in broadly defined regions of the country that are presumed to be meteorologically similar. Although procedures for estimating PMP are well-documented and in wide use, estimates of PMP and the resultant estimates of PMF commonly are controversial, particularly for sites where evidence of large storms and large historical floods may be lacking. The controversy is difficult to address because the probability of exceedance of the PMP storm is unknown and may be variable from site to site. Without knowing the probability of exceedance of the PMP or the PMF storm, accurate assessment of risk is not possible.

To better evaluate risk of dam failure and establish a more consistent basis for spillway design, a synthetic design storm having depths and temporal characteristics that are based on probability of exceedance is highly desirable. Unfortunately, most individual precipitation stations have record lengths less than 100 years, and the low probabilities of annual exceedance (0.01 to 0.00001) of the storms required for conservative design cannot be reliably determined at any single station. A regional analysis of annual precipitation maxima in the State of Washington (Schaefer, 1990), however, determined that data from individual precipitation stations could effectively be pooled within homogeneous regions. Based on the successful pooling of data, the effective record length within regions was extended to several thousand station-years. Thus, within homogeneous regions, extreme annual precipitation maxima (storm depths) having the necessary low probabilities of annual exceedance can be reasonably estimated from the pooled data. A second study in Washington (Schaefer, 1989) analyzed the temporal characteristics of extreme storms in Washington and developed dimensionless depth-duration frequency curves. Procedures also were developed for using the calculated storm depths for selected low probabilities of exceedance together with the dimensionless depth-duration curves for various exceedance probabilities to construct synthetic storms for design purposes. The results of the work in Washington have enabled dam-safety engineers to more reliably ascertain the risks associated with various spillway design alternatives and to reduce costs in many cases by using risk-based designs that were more cost-effective than those required by use of the deterministic PMP-based design standard.

Purpose and Scope

Based on the success of the studies in Washington, the U.S. Geological Survey, in cooperation with the Montana Dam Safety Section of the Montana Department of Natural Resources and Conservation (DNRC), undertook a study to: (1) conduct a regional analysis of annual precipitation maxima in Montana and (2) develop dimensionless depth-duration curves and procedures for constructing large synthetic storms for design purposes. This report describes the methods and results of the regional analysis.

The regional analysis was based on annual precipitation-maxima data for storm durations of 2, 6, and 24 hours. An annual precipitation maximum at a precipitation station for a specified duration, such as 2 hours, is the maximum precipitation amount, in inches, recorded during any 2-hour reporting period during the year. For purposes of this report, the term "annual precipitation maximum" is equivalent to "storm depth" or "precipitation depth for some specified duration" and the terms may be used interchangeably. For the 2-hour duration, annual maxima from 115 hourly recording stations in Montana and 4 hourly recording stations in Wyoming were used in the analysis. Data from Idaho were initially considered for inclusion in the database, but a preliminary analysis by the Montana Department of Natural Resources and Conservation (Gary R. Fischer, oral commun., 1995) indicated that storm characteristics were significantly different in Idaho than in Montana. The difference presumably is due to the greater influence of Pacific Ocean based winter storms in Idaho than in Montana. Data from North Dakota and Canada also were considered for inclusion, but considerably more data compilation and reduction would have been required to make those data usable. For the 6-hour and 24-hour durations, annual maxima from 118 hourly recording stations in Montana and 4 hourly recording stations in Wyoming were used. In addition, data from 337 daily recording stations, 22 of which were in Wyoming, were used for the analysis of 24-hour duration storms. All hourly recording stations and 283 of the daily recording stations were operated by the National Weather Service (NWS), while 54 of the daily recording stations were operated by the Natural Resources Conservation Service (formerly the Soil Conservation Service). Sites operated by the Natural Resources Conservation Service, commonly referred to as SNOTEL sites, were included in this study to obtain more precipitation data for the mountainous areas of the State. All sites had at least 10 years of annual-maximum precipitation data. The location and type of precipitation station are shown on plate 1 at the back of the report, and the stations and supplementary information are listed in table 1 at the back of the report.

L-moment statistics (Hosking, 1990) were computed for the at-station annual precipitation maxima and used to help determine homogeneous regions using procedures developed by Hosking and Wallis (1993). Within each homogeneous region, a probability distribution was selected based on *L*-moment statistics for dimensionless values of pooled at-site annual precipitation maxima for each duration. The at-site annual maxima for each duration were made dimensionless by dividing by the at-site mean values of annual maxima. The selected probability distributions were used to prepare dimensionless regional frequency curves. The dimensionless regional frequency curves are presented in terms of recurrence intervals rather than exceedance probabilities. The reciprocal of exceedance probability is equal to recurrence interval. For example, an annual precipitation maxima with an exceedance probability of 0.01 has a recurrence interval of 100 years. The equivalent record lengths for the combined at-site data were estimated for each duration within each region and were used as an indication of the relative reliability of the regional frequency curves.

To enable the dimensionless regional frequency curves to be used to estimate precipitation depths at ungaged sites for 2- , 6- , or 24-hour storms, a method for estimating mean values of 2- , 6- , or 24-hour duration precipitation depths was required. Accordingly, regression equations relating mean values of storm depths to various precipitation station characteristics (latitude, longitude, and mean annual precipitation) were developed.

Acknowledgment

Throughout the course of this study, Dr. Melvin G. Schaefer, Washington Department of Ecology, provided insight and encouragement to the author. Dr. Schaefer also reviewed portions of the data analysis and interpretation and offered technical advice that was appropriate and helpful. His timely and cheerful assistance is gratefully acknowledged.

DATABASE OF ANNUAL PRECIPITATION MAXIMA

Annual precipitation-maxima data were obtained from several sources. The data required careful scrutiny to ensure that periods of missing record did not bias the reported annual maxima. In addition, various statistical tests were made to ensure that (1) annual daily maxima were equivalent to annual 24-hour maxima after application of a constant adjustment factor, (2) annual maxima based on different annual periods were equivalent, (3) records from stations located relatively close together could be combined, and (4) annual maxima were not serially correlated and were stationary over the general period of data collection (1900-92). Finally, the cross-correlation between annual maxima for each station-pair for each duration was calculated and compared with distance between stations in each pair.

Data Sources

Annual precipitation-maxima data for NWS stations previously had been compiled by the National Climatic Data Center and were obtained from the Montana Department of Natural Resources and Conservation (Gary Fischer, written commun., 1994). Hourly precipitation data from the National Climatic Data Center generally were available only for the period 1948 to the present. Annual precipitation-maxima data for NWS hourly stations operated before 1948 were previously compiled by the National Weather Service and were obtained from the Washington Department of Ecology (M.G. Schaefer, written commun., 1994). Daily precipitation data for SNOTEL stations were obtained from the Montana Natural Resources Information System (J.R. Stimson, written commun., 1994), and annual maxima were extracted and formatted to be compatible with data for National Weather Service stations. Data were available through 1992 for most currently operated SNOTEL stations and some NWS daily and hourly stations. Data were available through 1991 for most currently operated NWS stations.

Effects of Missing Periods of Record

Virtually all precipitation stations used in the study had some periods of missing record. Reported annual maxima for stations having missing record were likely to be incorrect and biased on the low side if the periods of missing record occurred during times of heavy precipitation. Accordingly, annual data having periods of missing record were carefully checked to ensure that the reported maxima for those years were true maxima. If a reported maximum for any duration could not be verified as the true maximum, the maximum for that duration for that year was excluded from subsequent analyses. Considerable judgment was required to decide whether a reported annual maximum was to be used or excluded. If a period of missing record was long but generally dry and in a season of low storm activity at nearby precipitation stations, the reported annual maxima for all durations were likely to be used. However, if even a short period of missing record coincided with heavy rains at nearby stations, the annual maxima were likely to be excluded.

During some periods of missing record at some stations, precipitation gages continued to collect precipitation that was not recorded. In those instances, the first recorded amount after a period of missing record commonly was the accumulated total for the period of missing record and not the amount for the observational period for the station (one hour for hourly stations; one day for daily stations). Reported maxima based on data accumulated during missing periods of record were likely to be incorrect and biased on the high side. Again, careful scrutiny and judgment were required to determine whether reported annual maxima having possible accumulation errors were to be used or excluded.

Test for Equivalency of Annual Daily and 24-hour Maxima

The use of annual precipitation-maxima data from the 337 daily stations for analysis of 24-hour duration data greatly expanded the number of stations and overall length of record (fig. 1) and resulted in a denser areal distribution of data. Moreover, the use of data from daily stations in the SNOTEL network enabled the only generally available high-elevation precipitation data in the State to be considered in the regional analysis (fig. 2). However, daily maximum precipitation generally tends to be less than 24-hour maximum precipitation, because daily maxima are determined for a fixed time period, typically midnight to midnight, that may not include the true maximum 24-hour period of rainfall. Previous studies (Miller and others, 1973; Weiss, 1964) found that at-site annual daily maxima generally were equivalent to at-site annual 24-hour maxima after the daily maxima were multiplied by a constant correction factor of 1.13.

To determine whether corrected daily maxima were equivalent to 24-hour maxima in Montana, data for 65 stations having at least 10 concurrent years of daily and 24-hour maxima were tested. A non-parametric, two-sided rank-sum test was used to compare paired values of annual 24-hour maxima and annual daily maxima multiplied by the 1.13 correction factor at each of the 65 stations. The results of the rank-sum tests are reported as p-values. A p-value is the probability of obtaining a sample test statistic as extreme as that observed under the hypothesis that the medians of the corrected daily maximum and 24-hour maximum are identical. For example, a sample test statistic with a p-value of 0.05 would be expected to occur about 5 times in 100 repeated trials if the sample pairs were randomly drawn from two populations with identical medians. The p-value was less than 0.05 (5 percent significance level) at 2 of the 65 stations (about 3 percent), indicating that annual daily maxima were different from annual 24-hour maxima. At a significance level of 5 percent, about 3 stations out of 65 could be expected to show a difference just by chance alone. Accordingly, it was concluded that annual 24-hour maxima and annual daily maxima, after multiplication by 1.13, were equivalent and could be combined.

Test for Equivalency of Annual Maxima Based on Different Annual Periods

The hourly and daily precipitation data were obtained from different sources and, in some instances, the sources used different months to separate annual periods in the different data sets. Specifically, annual maxima for hourly data obtained from the National Climate Data Center were based on a climatic year beginning in September, whereas annual daily maxima obtained from the National Climate Data Center were based on the calendar year beginning in January. Annual daily maxima from SNOTEL stations were based on the water year beginning in October. To ensure that the annual maxima based on years with different beginning months were equivalent, annual maxima for 2-, 6-, and 24-hour duration data for 20 randomly selected sites were recompiled based on the calendar year . The recompiled data were compared to the annual maxima based on the climatic year using a two-sided rank-sum test. At each site, the annual maxima for each duration for the annual periods with different beginning months were found to be not significantly different. The smallest p-value for any duration was 0.09, while the largest p-value was 1.00. The p-values generally were greater than 0.7, clearly indicating that the differences between annual maxima

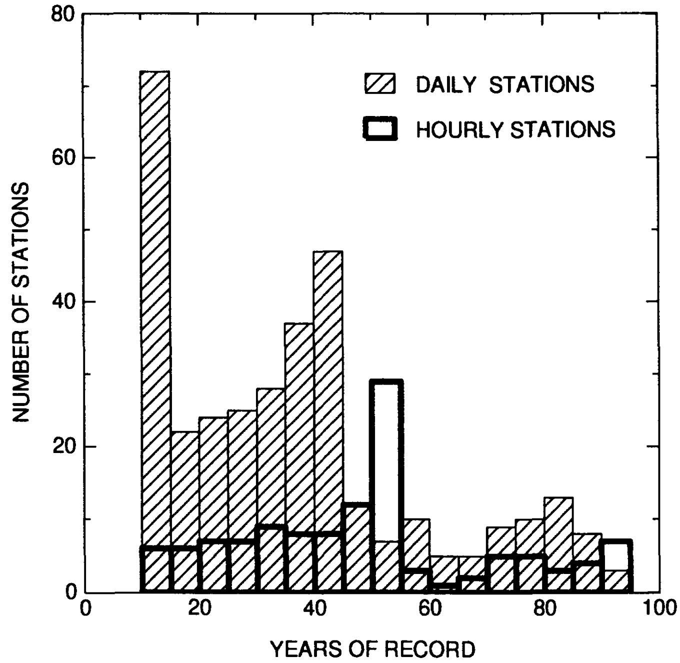

Figure 1. Types of annual-maxima precipitation stations and lengths of record, Montana and northern Wyoming.

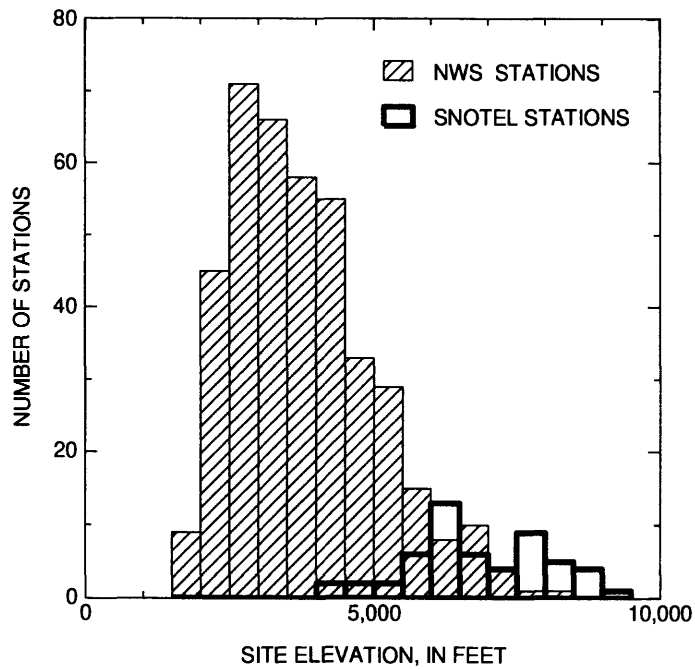

Figure 2. Types of annual-maxima precipitation stations and site elevations, Montana and northern Wyoming.

based on years with different months were not significant at the 20 test sites. This is consistent with findings by Schaefer (M.G. Shaefer, Washington Department of Ecology, oral commun., 1995) regarding analysis of annual maxima. Based on the clear indication of no difference between maxima determined from a climatic year and a calendar year, it was assumed that the same clear indication of no difference would result from a comparison between water year and calendar year or between water year and climatic year. Accordingly, annual maxima based on annual periods with different beginning months were considered to be equivalent for all stations used in the study.

Combining Records from Nearby Sites

Over the course of their operation, NWS stations occasionally are moved to new locations relatively close to the old locations. In addition, new stations may begin operation only a relatively short distance away from existing stations. If the distance and difference in elevation between nearby stations are small, their records can be considered to be equivalent and combined into one longer record. For this study, records from 7 pairs of stations were combined because these paired stations were less than 10 miles apart and less than 150 feet different in elevation. In addition, annual maxima from paired stations that were up to 20 miles apart and had elevation differences up to 320 feet were compared using the two-sided rank-sum test, and data from station pairs that did not have significantly different median values of precipitation maxima also were combined. Because the tested median values commonly were from different periods of record that might be expected to have different means simply because of the record difference, the significance level of the rank-sum test was set to 0.25. This relatively large value of significance level helped to minimize the possibility that the null hypothesis (medians are equal and station records can be combined) would incorrectly be accepted. Seven stations had their records extended as a result of the rank-sum comparison with nearby stations. Table 2 shows stations for which records of annual maxima were extended by the addition of data from nearby stations.

At one station (247159) shown in table 2, one large recorded annual storm depth from a nearby short-term station was added to the record even though the stations had substantially different elevations and mean values of precipitation maxima. The recorded value, known to be from a large general storm that caused significant flooding in a large area of west-central Montana, was from a station that did not have the required record length for inclusion in the study. The recorded value was added to the record at a station with a higher elevation that was not in operation during the large storm to ensure that the large storm would be considered. Because the higher-elevation station (247159) probably would have recorded a storm depth at least as large as the value recorded at the nearby lower-elevation station, the addition of the single large value was not considered to have unduly biased the record at station 247159.

Table 2. Precipitation stations for which records were extended by addition of data from nearby stations, Montana

Station (plate 1)	Original record length (years)	Extended record length (years)	t-test used to determine if records could be combined?
240199	10	85	Yes
241500	13	42	Yes
243996	31	93	Yes
244983	29	92	No
245337	64	86	Yes
245735	26	90	Yes
246302	73	91	Yes
246472	36	87	No
246691	23	42	No
247159	28	29	No
247267	12	39	No
247501	31	49	Yes
248233	35	44	No
248313	2	26	No
248866	10	68	No

Tests for Serial Correlation and Stationarity of Annual Precipitation Maxima

The methods of regionalization of annual precipitation maxima in this study are based on the assumption that the recorded values of annual maxima are independent and random events that have no significant serial correlation or trends over time (non-stationarity). To determine whether the annual data were serially correlated, the lag-one (serial) correlation coefficient was computed for the annual precipitation maxima for each duration at each station. For each duration, the mean value of serial correlation coefficient was computed and tested for significance against the null hypothesis that the mean value is zero. As shown in table 3, the mean values of serial correlation coefficient for 2-, 6-, and 24-hour duration annual maxima were all close to zero. The p-values for attained level of significance were substantially greater than 0.05 for all durations, clearly indicating that the null hypothesis could not be rejected. On this basis, the annual precipitation maxima were considered to have no significant serial correlation.

Table 3. Mean value of serial correlation coefficient and attained significance level for annual precipitation maxima in Montana

Duration, in hours	Mean value of serial correlation coefficient	p-value
2	0.0003	0.99
6	-.0179	.25
24	-.0051	.56

To determine whether recorded annual precipitation maxima were stationary over the general period of data collection (1900-92), stations having the longest periods of record for each duration were selected for testing. For 2-hour and 6-hour duration data respectively, 55 stations and 64 stations that had periods of record greater than 40 years were selected. For the substantially larger 24-hour-duration data base, 54 stations that had more than 75 years of record were selected. For each duration, each recorded annual precipitation maximum at each test station was divided by the mean value for the period of record, and the resultant dimensionless values of precipitation maxima at each station were regressed against the year of occurrence minus 1900. Thus, for the 2- , 6- , and 24-hour durations respectively, 55, 64, and 54 separate regressions were made. The slope of each regression line, if determined to be significantly different from zero, indicates the magnitude of trend in annual precipitation maxima over time at each station. Table 4 presents the results of the regressions for each duration and provides an overall indication of the stationarity of the annual precipitation maxima.

Table 4. Results of regression analyses for trend in annual precipitation maxima over time for selected stations in Montana

Duration, in hours	Number of regressions (number of stations)	Average slope of regression line, in percent of mean value of annual maxima	Number of regressions where p-level of significance of regression slope was less than 0.05
2	55	0.00075	2
6	64	.00253	3
24	54	.00277	8

As shown in table 4, the average slope of the regression lines for each duration is close to zero, ranging from 0.00075 percent of the long-term mean value for 2-hour duration annual maxima to 0.00277 percent of the long-term mean value for 24-hour duration annual maxima. For both the 2-hour and 6-hour duration data, less than 5 percent of the regressions had slopes that were significantly different from zero, indicating that, overall, trends in annual maxima are not significant. For the 24-hour duration annual maxima, almost 15 percent of the regressions had slopes significantly different from zero, indicating that, overall, the trend might be different from zero. However, for the eight regressions for 24-hour annual maxima that had slopes significantly different from zero, four had positive slopes and four had negative slopes. Thus, while a trend may be more somewhat more likely for 24-hour duration data, no clear indication of the direction of trend is apparent. For purposes of this study, it was concluded that trends in annual precipitation maxima over the general period of data collection (1900-92) were not significant for any of the durations and that annual maxima thus could be considered to be stationary.

Interstation Correlation

To determine the degree of spatial independence of the database, the interstation correlation coefficient was calculated for the concurrent recorded annual maxima for every station pair for each duration. Based on the calculations, 6,409 values of interstation correlation coefficient, which have a mean of 0.037, were calculated for the 2-hour duration. For the 6-hour duration, 6,625 values of interstation correlation coefficient, which have a mean of 0.057, were calculated. For the 24-hour duration, 91,189 values, which have a mean of 0.074, were calculated. For all durations, the mean values, although small, were significantly different from zero (p-values all equal to 1.00). The distributions of the interstation correlation coefficients for each duration are displayed as box plots in figure 3. The results in figure 3 indicate that the interstation correlation is least for 2-hour duration annual maxima and greatest for 24-hour duration annual maxima. Given that longer duration storms (24-hours) tend to be large-scale, general storms that cover larger areas than the smaller-scale, convective storms with shorter durations (2- and 6-hours), the somewhat larger values of interstation correlation for longer durations appear to be reasonable.

To determine whether the interstation correlation coefficient is related to distance between sites, scatterplots of paired values of interstation correlation coeffi-

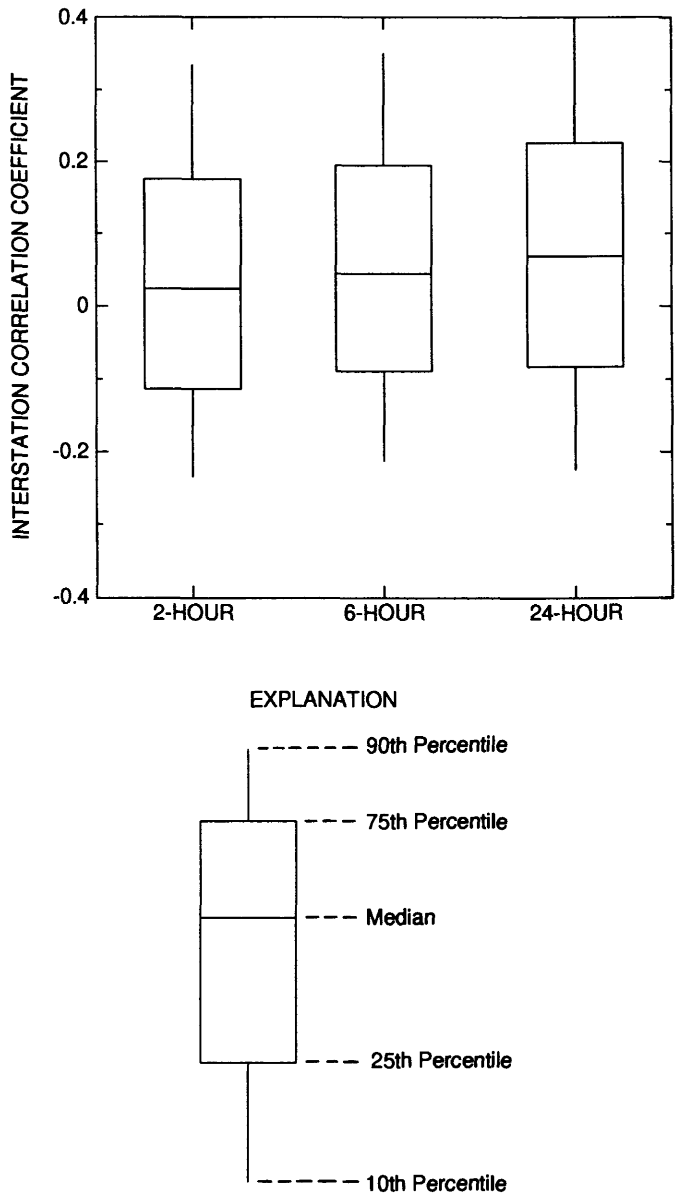

Figure 3. Distribution of interstation correlation coefficients by duration for annual precipitation maxima, Montana and northern Wyoming.

cient and distance were made for each duration, and LOWESS smooth lines (Helsel and Hirsch, 1992, p. 288-291) fit to the paired data. A LOWESS line, like a regression line, indicates a relation between two variables. Unlike a regression line, however, a LOWESS line does not require a linear relation. A scatterplot of a small sample of the paired values for the 24-hour duration and the LOWESS line relating interstation correlation coefficient to interstation distance is shown on figure 4. The LOWESS lines for the 2-, 6-, and 24-hour durations are compared on figure 5. As shown on figure 4, the LOWESS line for 24-hour duration data does indicate a tendency for interstation correlation to increase with decreasing interstation distance, but, based on the large amount of scatter in the data, the relation is poor. Evidently, many other factors in addition to interstation distance affect the degree of interstation correlation and, hence, the spatial independence of annual precipitation maxima. The comparison of LOWESS lines for the three durations shown in figure 5 indicates that the relation between interstation correlation and distance is similar for each duration and that the spatial independence of annual precipitation maxima generally increases with decreasing duration. Overall, it is concluded that annual precipitation maxima are not completely spatially independent and that the degree of dependence is related to storm duration and distance between stations. Although the degree of spatial dependence is small and considered to have no significant effects on the methods of regionalization used in this study (Hosking and Wallis, 1988), it does indicate that the amount of regional information available may be less than that indicated by the total number of station-years of record. The effect of spatial dependence on equivalent record length within regions will be discussed later in the report.

REGIONAL ANALYSIS APPROACH

The regional analysis approach is based on the concept that at-site data can be pooled within regions that are "homogeneous." In this context, homogeneous is taken to mean that probability distributions and their

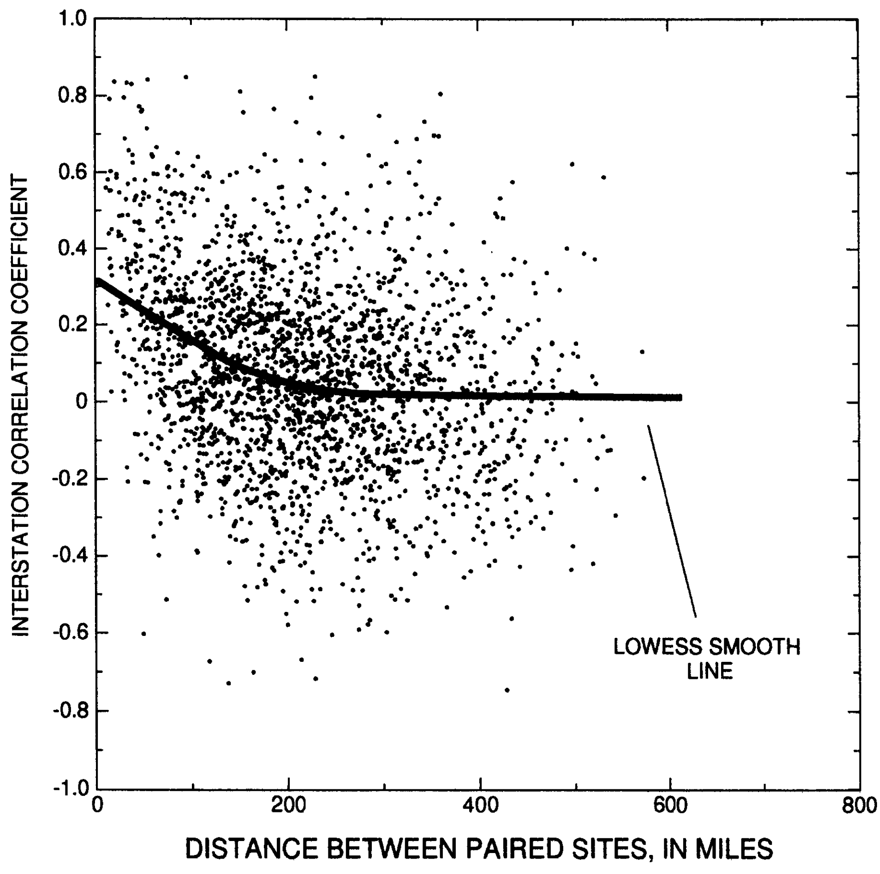

Figure 4. Relation between interstation correlation coefficient and distance between sites for 24-hour duration annual precipitation maxima, Montana and northern Wyoming.

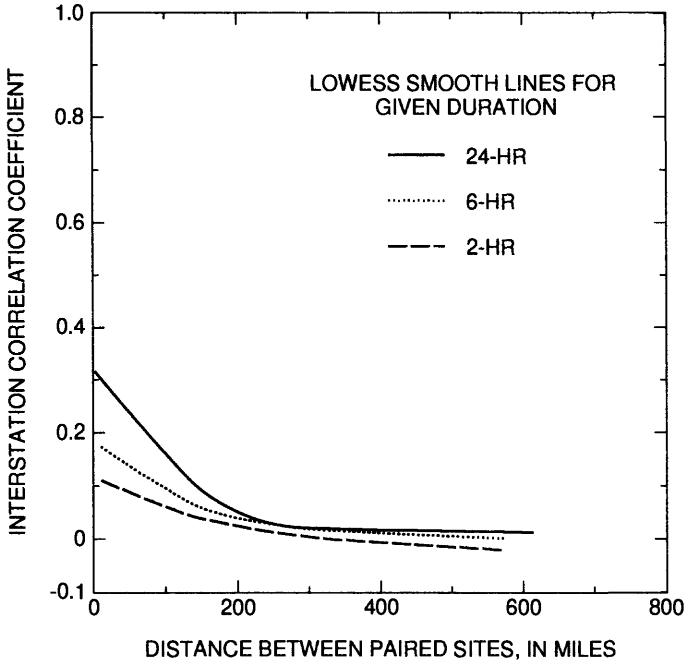

Figure 5. LOWESS trend lines for interstation correlation coefficient versus distance between sites for annual precipitation maxima, Montana and northern Wyoming.

resultant frequency curves for at-site data are identical, except for a site-specific scaling factor, at all sites in a region. The at-site mean value commonly is used as the scaling factor in regional analyses. Key elements in a regional analysis include: (1) determination of homogeneous regions, (2) determination of regional frequency curves, and (3) a method for estimation of the at-site mean (scaling factor) at any location in a region. The use of *L*-moment statistics aids in completion of the first two elements. The following sections include brief discussions of the theories of regional frequency curves and *L*-moments and the application of the key elements of a regional analysis to the current study in Montana.

Theory of Regional Frequency Curves

In flood-frequency analysis, the use of dimensionless frequency curves within homogeneous regions is well documented (Dalrymple, 1960; Wallis, 1989). In recent years, dimensionless frequency curves have increasingly been used in analyses of precipitation maxima (Alila and others, 1992; Hosking and Wallis, 1993; Schaefer, 1990; Vogel and Lin, 1992). The mean value of the at-site annual floods or storm depths was used as the scaling factor in each of these studies.

In general, for an analysis of storm depths, the quantiles Q of non-exceedance probability F at any site i in a region (Hosking and Wallis, 1993) can be expressed as:

$$Q_i(F) = \mu_i q(F) , \qquad (1)$$

where

$Q_i(F)$ is the quantile of non-exceedance probability F at site i,

μ_i is the mean value of storm depth at site i, and

$q(F)$ is the regional quantile of non-exceedance probability F.

The regional quantiles $q(F)$, $0 < F < 1$, form a "regional growth curve" that is common to all sites in the region.

Determination of the regional quantiles, $q(F)$, in equation (1) is dependent upon the type of probability distribution that fits the regional data. For example, the relation between the quantile function and the 3-parameter Generalized Extreme Value (GEV) probability distribution (Hosking, 1990) is as follows:

$$q(F) = \xi + \alpha (\{ 1 - (-\log F)^k \} / k) , \qquad (2)$$

where

ξ, α, and k are the parameters of the GEV distribution, and

$\log F$ is the natural logarithm of non-exceedance probability.

Hosking (1990) provides equations for estimating the parameters of various probability distributions from the L-moments and L-moment ratios of the data. For regional data, L-moments and L-moment ratios for each site are weighted by record length and averaged in order to calculate parameters of the regional probability distribution. Herein, the term average as applied to L-moments or L-moment ratios means a record-length weighted average.

Regional growth curves are analogous to dimensionless regional frequency curves, except that frequency curves typically are expressed in terms of recurrence intervals rather than non-exceedance probabilities. For annual maxima, recurrence interval, in years, can be simply determined as the reciprocal of 1 minus the non-exceedance probability. In addition, frequency curves typically are plotted on special forms of probability plotting paper that tend to linearize the curves.

To plot the regional growth curves as regional dimensionless frequency curves, the non-exceedance probabilities are first converted to Gumbel reduced variates by using the following equation (Hosking and Wallis, 1993):

$$GRV = -\log(-\log F) \,, \quad (3)$$

where

GRV is the Gumbel reduced variate corresponding to non-exceedance probability *F*.

Plotting regional quantiles on the ordinate (Y axis) and uniformly spaced values of *GRV* on the abscissa (X axis) has the same linearizing effect as plotting the regional growth curve on extreme-value plotting paper. The plots of regional quantiles versus *GRV* take the form of regional frequency curves when, after plotting, *GRV* are converted to recurrence intervals, commonly expressed as *T-year*, using the following equation:

$$T\text{-}year = \frac{1}{[1 - e^{(-e)^{GRV}}]} \,. \quad (4)$$

Estimation of the dimensionless storm depth having a *T-year* recurrence interval at any site within a homogeneous region can then be obtained from the regional frequency curve. Multiplication of the dimensionless storm depth by the at-site mean yields the *T-year* at-site storm depth.

Theory of Regional *L*-moments

L-moments, like conventional moments, are used to summarize theoretical probability distributions and observed samples. L-moments, however, are computed as linear combinations of the ranked observations and do not require that the observations be squared and cubed as do conventional moments (Stedinger and others, 1992). As a result, L-moments are more robust and unbiased than conventional moments and provide more reliable estimates of the parameters of probability distributions than do conventional moments. This is particularly important for precipitation data which are characterized by large values of skewness and kurtosis.

The first L-moment estimator, l_1, is the mean, which can be expressed in terms of expected value as (Stedinger and others, 1993):

$$l_1 = E(X), \quad (5)$$

where $E(X)$ is the expected value of some variable X.

If $X_{(i|n)}$ is the ith-largest observation in a sample of size n (i = 1 corresponds to largest), then the second L-moment is based on the expected difference between two randomly selected observations (Stedinger and others, 1993):

$$l_2 = \frac{1}{2} E\left[X_{(1|2)} - X_{(2|2)}\right]. \quad (6)$$

Similarly, the third and fourth L-moments are defined as follows (Stedinger and others, 1993):

$$l_3 = \frac{1}{3} E\left[X_{(1|3)} - 2X_{(2|3)} + X_{(3|3)}\right] \text{ and,} \quad (7)$$

$$l_4 = \frac{1}{4} E\left[X_{(1|4)} - 3X_{(2|4)} + 3X_{(3|4)} - X_{(4|4)}\right]. \quad (8)$$

Three L-moment ratios that are needed to describe probability distributions and apply various statistical tests are defined in terms of the first four L-moments as follows:

$t_2 = l_2/l_1$ = L-coefficient of variation (L-CV),
$t_3 = l_3/l_2$ = L-skewness (L-Skew), and
$t_4 = l_4/l_2$ = L-kurtosis (L-Kurtosis).

These L-moments and L-moment ratios are analagous to their counterparts defined for conventional moments. Hosking and Wallis (1993) describe three statistical tests based on L-moments that are used to help identify homogeneous regions and the appropriate probability distributions for use in those regions. These tests are briefly described in the following sections.

Discordancy Test

The discordancy test is used to identify sites that are grossly discordant from the group as a whole. The discordancy measure is based on the L-moments of the sample data and is defined as

$$D_i = \frac{N}{3(N-1)}\left(\mathbf{u}_i - \bar{\mathbf{u}}\right)^T \mathbf{S}^{-1}\left(\mathbf{u}_i - \bar{\mathbf{u}}\right), \qquad (9)$$

where

D_i is the discordancy measure for site i,

N is the number of sites in the group,

$\bar{\mathbf{u}}_i$ is the vector of L-CV, L-Skew, and L-Kurtosis for site i,

$\mathbf{u}$ is the mean of vector $\mathbf{u}_i$,

$\mathbf{S}$ is the sample covariance matrix of $\mathbf{u}_i$.

A site is considered to be discordant if D_i is greater than 3. Hosking and Wallis (1993) provide the background and theory for the test, which is used to identify sites that may not be consistent with other sites in a group and may need to be moved to another group.

Heterogeneity Test

The heterogeneity test described by Hosking and Wallis (1993) is used to estimate the degree of heterogeneity in a group of sites and to assess whether they might reasonably be considered to compose a homogeneous region. Specifically, the heterogeneity measure, H, compares the between-site variations in sample L-moments for the group with the variations that would be expected for a homogeneous region. The heterogeneity measure is defined as

$$H = \frac{(V - m_v)}{s_v}, \qquad (10)$$

where

V is the standard deviation, weighted by record length, of L-CV for sites in the group,

m_v, s_v are the mean and standard deviation of a large number of Monte Carlo simulations of V.

A group of sites generally is considered to be homogeneous if $H < 2$. The Monte Carlo simulations, usually 500 in number, are performed using a 4-parameter Kappa distribution applied to a hypothetical homogeneous region where the sites have record lengths and average L-moments the same as those of the group being tested (Hosking and Wallis, 1993).

Goodness-of-fit Test

The goodness-of-fit test is used to determine whether a particular probability distribution fits the regional data acceptably close. Five 3-parameter distributions generally are evaluated: Generalized Extreme Value (GEV), Generalized Logistic (GLO), Generalized Normal (GN), Pearson Type III (PEAR), and Generalized Pareto (GP). The Wakeby distribution, a 5-parameter distribution, is also evaluated for use if no 3-parameter distribution is considered to be acceptable. The goodness-of-fit test is defined as

$$Z^{DIST} = \frac{\left(\bar{t}_4 - t_4^{DIST}\right)}{s_4}, \qquad (11)$$

where

Z^{DIST} is the goodness-of-fit measure for some distribution, $DIST$,

$\bar{t}_4$ is the mean L-Kurtosis, corrected for bias, (Hosking and Wallis, 1993) for a group of sites,

t_4^{DIST} is the mean L-Kurtosis of the fitted distribution, $DIST$,

s_4 is the standard deviation of L-Kurtosis based on 500 simulations previously described.

In general, a distribution is considered to have a good fit if $|Z^{DIST}| < 1.64$. As noted by Hosking and Wallis (1993), this criterion is somewhat arbitrary and may be unreliable if relatively high serial or interstation correlation is present in the data.

Determination of Homogeneous Regions

Determination of acceptable homogeneous regions commonly requires several attempts. The first attempts for the current study were based on a unique, "super-region" approach used in Washington. The final delineation of homogeneous regions for Montana generally was based on physiography and climate.

Super-Region Approach

In Washington State, Schaefer (1990) found that sites could be grouped into homogeneous regions for the analysis of annual precipitation maxima if they had similar values of mean annual precipitation. Thirteen regions within which the at-station mean annual precipitation varied over a narrow range were thus determined to be homogeneous in Washington (M.G. Schaefer, written commun., 1994). Further, Schaefer found that the statistical parameters used to define the regional probability distributions varied systematically across the State in the same manner as mean annual precipitation varied across the State. Functional relations between mean annual precipitation and parameters of the Kappa probability distribution were developed so that the entire State could be treated as a homogeneous "super-region" within which a single probability distribution was applicable. On this basis, Schaefer was able to avoid the problem of abrupt geographical boundaries between homogeneous regions and the difficulties in estimation that often result near such boundaries.

As a result of Schaefer's work in Washington, the first attempt at definition of homogeneous regions for the analysis of annual precipitation maxima in Montana was based on the grouping of sites having similar values of mean annual precipitation. The 24-hour duration data were used in all attempts to determine homogeneous regions in Montana because of the much greater number of sites and better spatial coverage, particularly in mountain areas, of the 24-hour data. Thus, 6 groups having the following ranges in value of mean annual precipitation were tested for heterogeneity: (1) less than 12 inches, (2) between 12 and 15 inches, (3) between 15 and 20 inches, (4) between 20 and 25 inches, (5) between 25 and 30 inches, and (6) greater than 30 inches. The results of the heterogeneity tests indicated that none of the 6 groups could be considered homogeneous ($H < 2$). Moreover, the average L-moment ratios (L-CV, L-Skew, and L-Kurtosis) for the six groups did not systematically vary with mean annual precipitation as they did in Washington. Determination of a homogeneous super-region based on mean annual precipitation thus was considered not to be feasible for Montana.

Site elevation was also tried as a super-region grouping variable in the same fashion as was mean annual precipitation. Thus, five groups whose sites had elevations within ranges of 1,000 feet were tested for heterogeneity. Only one of the five groups was found to be homogeneous ($H < 2$). Heterogeneity test values for the other four groups ranged from 2.56 to 7.35. In addition, the L-moment ratios did not vary systematically with site elevation. Determination of a homogeneous super-region on the basis of site elevation also was considered not to be feasible for Montana.

Physiographic and Climatic Approach

In previous flood-frequency studies in Montana (Omang, 1992; Omang and others, 1986), physiography and climate were used in a general way to delineate eight regions within which flood-frequency characteristics were considered to be similar. For the current study, the same eight regions were tested for heterogeneity of 24-hour annual precipitation maxima. Three regions were found to be homogeneous ($H < 2$). Heterogeneity test values for the other five regions ranged from 2.63 to 4.54. Various combinations and modifications of the eight regions, including the removal of sites having large discordancy values, were also tested for heterogeneity. In some instances, the test result for heterogeneity improved as a result of the modifications; in other instances, the heterogeneity-test result worsened. Overall, the use of the same or modified regions for the analysis of annual precipitation maxima as for the analysis of flood frequency was considered not to be feasible.

In an unpublished report on flood frequency (P.E. Farnes, formerly with Natural Resources Conservation Service, written commun., 1994), Farnes used physiography and climate to delineate three regions for which large storm characteristics appeared to be generally distinct. These three regions, with minor modifications (pl. 1, at the back of the report), were tested and found to be acceptably homogeneous for purposes of this study. Region 1 is a largely mountainous area in western Montana where large, general storms commonly receive their moisture from the Pacific Ocean and generally move in an easterly direction. Most large storms in this region occur in the spring (April-June), but occasionally occur during fall and winter. Region 2 generally consists of a relatively narrow band of mountains running largely north-south along the eastern edge of the Rocky Mountains and includes two isolated small mountainous areas east of the contiguous band. Moist airmasses that cause large, general storms in this region often arise in the Gulf of Mexico during May and June and produce large amounts of precipitation from orographic effects when they collide with cold air masses over the mountains. Fall and winter storms that originate from Pacific moisture occur less frequently in Region 2 than in Region 1. Region 3 is composed of the plains areas of eastern Montana. Large storms in this region may receive moisture from either Pacific or Gulf sources. Large winter storms rarely occur in Region 3. Orographic effects are not a factor in storm generation in this region, but summer convective storms may be more intense than in the other two regions because of generally higher daytime temperatures.

Results of the initial heterogeneity tests for these three regions are shown in table 5 and indicate that for the 24-hour duration none of the regions was homogeneous. Although these results are seemingly no better

Table 5. Results of heterogeneity tests and regional average *L*-moment ratios for 24-hour duration annual precipitation maxima in Montana

Region	Number of sites	*H* value	*L*-CV	*L*-Skew	*L*-Kurtosis
1	149	3.58	0.187	0.200	.154
2	89	3.14	.220	.250	.189
3	221	2.46	.228	.220	.159

Table 6. Results of heterogeneity tests and regional average *L*-moment ratios for 2-hour duration annual precipitation maxima in Montana

Region	Number of sites	*H* value	*L*-CV	*L*-Skew	*L*-Kurtosis
1	44	0.13	0.212	0.276	0.224
2	24	1.72	.232	.288	.226
3	51	.56	.260	.272	.189

Table 7. Results of heterogeneity tests and regional average *L*-moment ratios for 6-hour duration annual precipitation maxima in Montana

Region	Number of sites	*H* value	*L*-CV	*L*-Skew	*L*-Kurtosis
1	46	-1.23	0.189	0.246	0.208
2	24	2.15	.207	.225	.184
3	52	.90	.232	.242	.187

than results previously described for other trial regional groupings, the maximum heterogeneity test value (H = 3.58) was smaller than that for the other groupings. In addition, Regions 1, 2, and 3 each contained more than 75 sites. Previous trial regions that had 75 or more sites also were all determined to be heterogeneous. As noted by Hosking and Wallis (1993, p. 276), the test value for heterogeneity tends to be correct for large sample size, but may falsely indicate homogeneity for small sample size. On that basis, findings of homogeneity for previous trial regions, all of which had sample sizes smaller than 75, may not be correct.

An additional reason for the relatively large heterogeneity test values for 24-hour duration data is that many of the relatively short-record SNOTEL sites were found to be discordant. When the discordant sites were removed from the database and the heterogeneity tests re-run, H values for Regions 1 and 2 were reduced to 2.84 and 1.80, respectively. Nevertheless, because it could not be determined whether the discordancy of the SNOTEL sites was due to their unique, high-elevation, mountainous locations or their relatively short record lengths, it was considered more important to retain those sites in the database for their uniqueness than to improve regional homogeneity by excluding them. Most importantly, whether the sites were retained or excluded, the regional average *L*-CV, *L*-Skew, and *L*-Kurtosis were not significantly different, so the overall effect of the discordant SNOTEL sites on the regional frequency curves was considered to be slight.

In general, Regions 1, 2, and 3 were considered to be more nearly homogeneous for the 24-hour duration than previous trial regions because the heterogeneity test values for Regions 1, 2, and 3 did not have such wide variation from region to region as those for the other trial regions. Regions 1, 2, and 3 also were considered to have a stronger physical basis for homogeneity based on such factors as precipitation source and storm direction, seasonality of storms, and orographic effects on storms than did other trial regions. Regions 1, 2, and 3 were divided into smaller regions based on elevation and tested for homogeneity in an attempt to more fully account for orographic effects, but test results did not improve. Overall, given the more consistent regional variation in H values, the effects of the unique SNOTEL sites, and the better physical basis for homogeneity, Regions 1, 2, and 3 were considered to be acceptably close to homogeneous regions for the 24-hour duration for purposes of this study and were further tested for homogeneity for the 2-hour and 6-hour durations.

Tables 6 and 7 summarize the heterogeneity test results for the selected three regions for 2- and 6-hour duration data and indicate that H values for the 2- and 6-hour data for all regions were substantially smaller than for the 24-hour duration. For the 2- and 6-hour duration data, all regions were found to be homogeneous on the basis of H values, except for Region 2 for the 6-hour duration.

BEHAVIOR OF REGIONAL *L*-MOMENT STATISTICS

To determine whether the regional average *L*-moment ratios varied consistently with duration for each of the three regions, plots of *L*-CV, *L*-Skew, and *L*-Kurtosis versus duration were made for each region (fig. 6-8). As shown on figures 6-8, *L*-moment ratios decreased with increasing duration except for Region 2, where *L*-moment ratios for the 6-hour duration data were smaller than for the 2-hour and 24-hour data. Preliminary analyses of regional frequency curves developed from the unadjusted *L*-moment ratios indicated that the shape of the 6-hour curve for Region 2 was inconsistent with the shape of all other regional curves. Much of this inconsistency could be traced to the magnitude of *L*-CV and *L*-Skew for 6-hour duration data in Region 2. Because the trend for decreasing *L*-moment ratios with increasing duration was clear for both Regions 1 and 3 and because the heterogeneity tests indicated that Region 2 was the most heterogeneous of the three regions for 6-hour duration data, the small *L*-moment ratios for 6-hour duration data in Region 2 were considered to be anomalous. To determine whether adjustments to the *L*-moment ratios for 6-hour duration data in Region 2 might reasonably be made, the upper limit of the 90-percent confidence interval for the regional average value of each *L*-moment ratio was calculated based on the standard deviation and number of at-site values (Helsel and Hirsch, 1992). As shown on figures 6-8, the regional average values for *L*-CV, *L*-Skew, and *L*-Kurtosis for 6-hour data in Region 2 could each be adjusted upward far enough to result in a smoothly decreasing curve without exceeding the value for the upper limit of the 90-percent confidence interval. On that basis, the adjustments to the *L*-moment ratios for Region 2 were considered to be reasonable and necessary in order to provide consistent relations between regional average *L*-moment ratios and storm durations and to provide consistency among regional frequency curves. The adjusted regional average values of *L*-CV, *L*-Skew, and *L*-Kurtosis for 6-hour data in Region 2 are shown in table 8. A review of table 8 shows the magnitudes of the adjustment to be relatively small.

Determination of Regional Frequency Curves

The regional average *L*-moment ratios were used to calculate parameters of five probability distributions (Hosking and Wallis, 1993), and the goodness-of-fit test was used as previously described to determine whether the distributions fit the regional data acceptably close. Goodness-of-fit tests were used for all durations and regions except for 6-hour duration data in Region 2 where *L*-moment ratios had been adjusted as previously described. For most regions and durations, more than one distribution met the goodness-of-fit

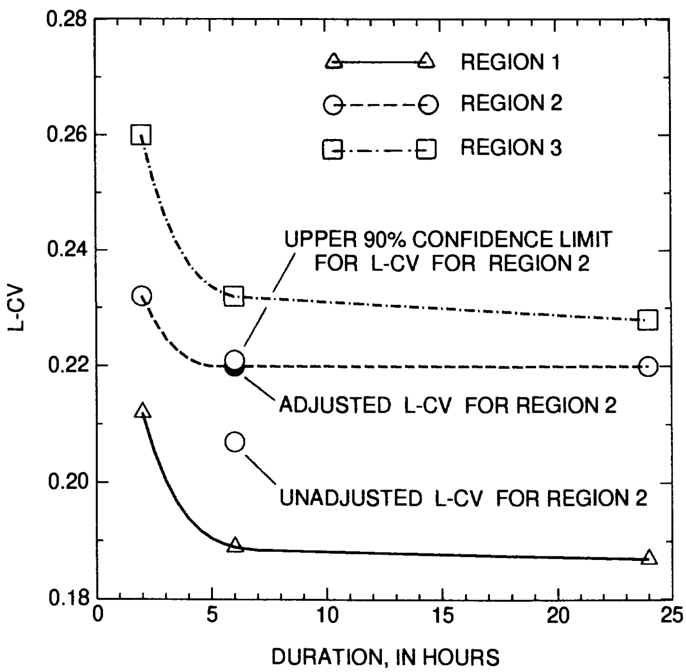

Figure 6. Relation between *L*-CV and duration of precipitation in each region and adjustment to regional average value of *L*-CV for 6-hour duration annual precipitation maxima in Region 2, Montana.

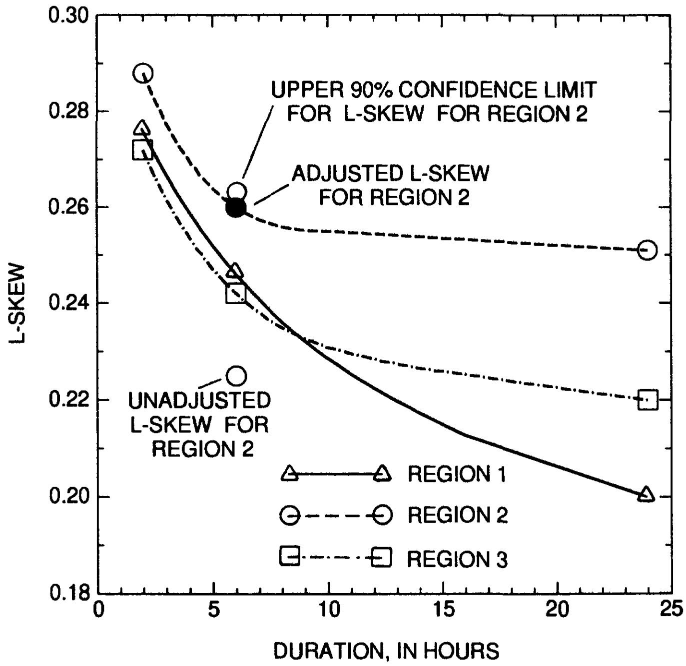

Figure 7. Relation between *L*-Skew and duration of precipitation in each region and adjustment to regional average value of *L*-Skew for 6-hour duration annual precipitation maxima in Region 2, Montana.

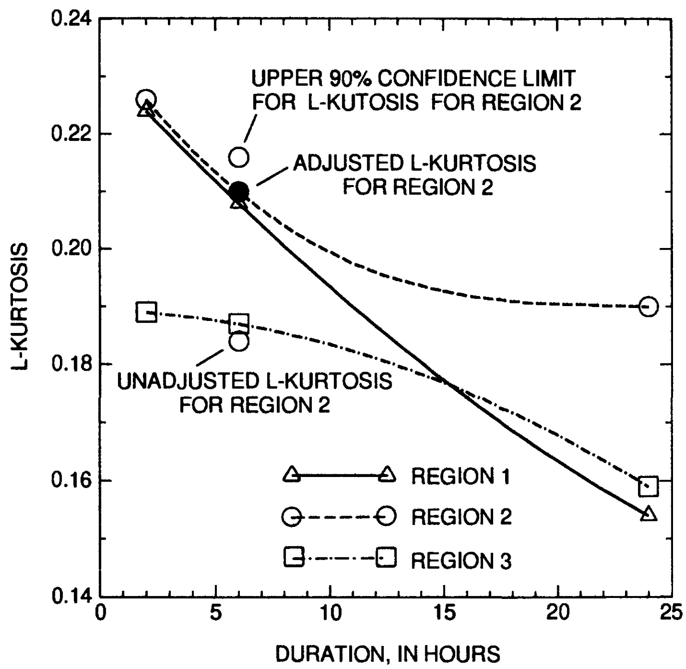

Figure 8. Relation between *L*-Kurtosis and duration of precipitation in each region and adjustment to regional average value of *L*-Kurtosis for 6-hour duration annual precipitation maxima in Region 2, Montana.

Table 8. Regional average *L*-moment ratios for 6-hour data in Region 2, Montana

	L-CV	*L*-Skew	*L*-Kurtosis
Unadjusted	0.207	0.225	0.184
Adjusted	0.221	0.260	0.210
Percent change	+6.8	+15.6	+7.1

criterion. The probability distribution that most often satisfied the goodness-of-fit test was the GEV. To ensure consistency among durations and regions, the GEV was selected as the appropriate distribution for use in all regions for all durations. For the 6-hour duration data in Region 2, the adjusted values of *L*-CV and *L*-Skew were used to calculate parameters of the GEV distribution. Table 9 shows the parameters of the GEV distribution for each region and duration.

L-moment ratio diagrams were prepared for each duration and region to provide a visual indication of how well the GEV distribution fit the regional data (figs. 9-11). In each figure, paired values of at-site *L*-Skew and *L*-Kurtosis were plotted together with the regional average paired value and lines representing the theoretical relation between *L*-Skew and *L*-Kurtosis for three probability distributions. A distribution is considered to have an acceptable fit to the regional data if the theoretical relation between *L*-Skew and *L*-Kurtosis is acceptably close to the regional average value. The three selected probability distributions, GEV, GLO, and GNO, were those most frequently found to satisfy the goodness-of-fit test. As indicated by figures 9-11, the regional average paired value of *L*-Skew and *L*-Kurtosis was relatively close to the line for the GEV distribution for all durations and regions.

While there is substantial scatter of L-moment data pairs in figures 9-11, this degree of scatter is entirely consistent with the variability expected from sample statistics. This same type of scatter was observed when computer simulations were used to generate data sets from known distributions with known population parameters (Hosking, 1990). The important feature in figures 9-11 is the relation between the regional mean and the GEV distribution line.

The values of the GEV parameters shown in table 9 were used in equation 2 to calculate regional quantiles for various non-exceedance probabilities up to 0.9998. Regional frequency curves were developed by plotting the calculated quantiles (Y axis) against selected results from equations 3 and 4 (X axis) and are shown on figures 12-14 grouped by region and on figures 15-17 grouped by duration. For example, using the GEV parameters in table 9 for 2-hour duration in Region 1 and solving equation 2 for a non-exceedance probability of 0.99 yields the following:

$$q(F) = \xi + \alpha\,(\{1 - (-\log F)^{k}\}/k)$$
$$q(0.99) = 0.803 + 0.258\,(\{1-(-\log 0.99)^{-0.159}\}/-0.159)$$
$$= 0.803 + 0.258\,(1-(0.010)^{-0.159})/-0.159)$$
$$= 0.803 + 0.258\,(1-2.080)/-0.159$$
$$= 0.803 + 0.258\,(-1.080)/(-0.159)$$
$$= 0.803 + 0.258\,(6.792)$$
$$q(0.99) = 2.55$$

The recurrence interval for a non-exceedance probability of 0.99 is 1/(1 - 0.99), or 100 years.

To make the frequency curve more linear, non-exceedance probability is converted to GRV using equation 3 as follows:

$$\text{GRV} = -\log(-\log F)$$
$$= -\log(-\log 0.99)$$
$$= -\log(0.010)$$
$$= 4.60$$

Thus, the quantile value, which corresponds to a dimensionless storm depth, is plotted 2.55 units from the origin on the Y-axis and 4.60 units, corresponding to a recurrence interval of 100 years, from the origin on the X-axis (figs. 12 and 15). After plotting the complete frequency curve, the X-axis labels are expressed in terms of recurrence intervals rather than GRV.

Table 9. Parameters for Generalized Extreme Value (GEV) distribution applied to 2- 6-, and 24-hour duration storm depths in Montana

[ξ, α, and **k** are parameters for the GEV distribution]

REGION	Duration, in hours								
	2			6			24		
	ξ	α	k	ξ	α	k	ξ	α	k
1	0.803	0.258	-0.159	0.830	0.242	-0.114	0.839	0.258	-0.047
2	.783	.276	-.176	.79	.275	-.135	.801	.280	-.120
3	.765	.314	-.150	.791	.300	-.109	.799	.304	-.076

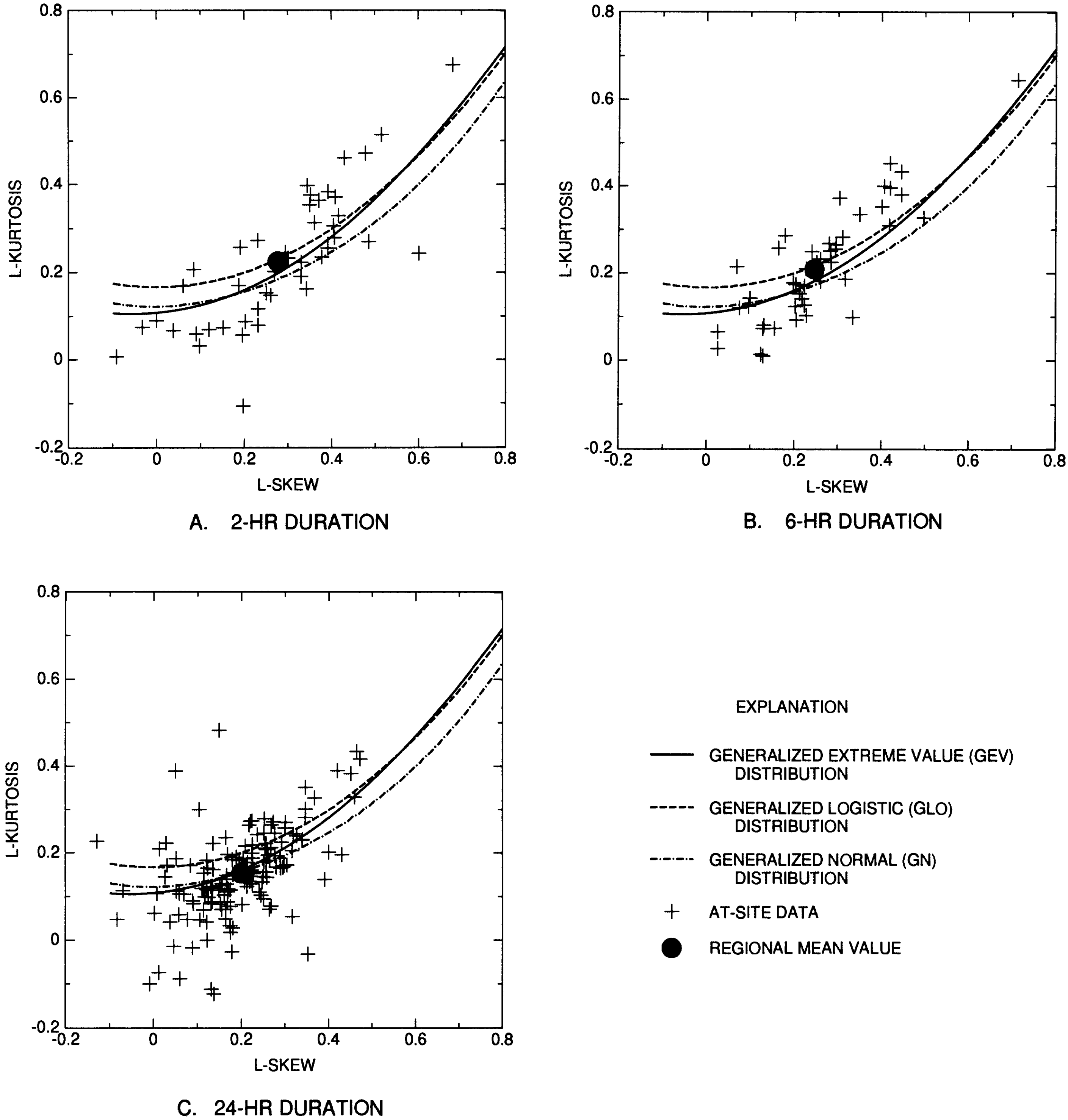

Figure 9. *L*-moment ratios for annual precipitation maxima in Region 1, Montana.

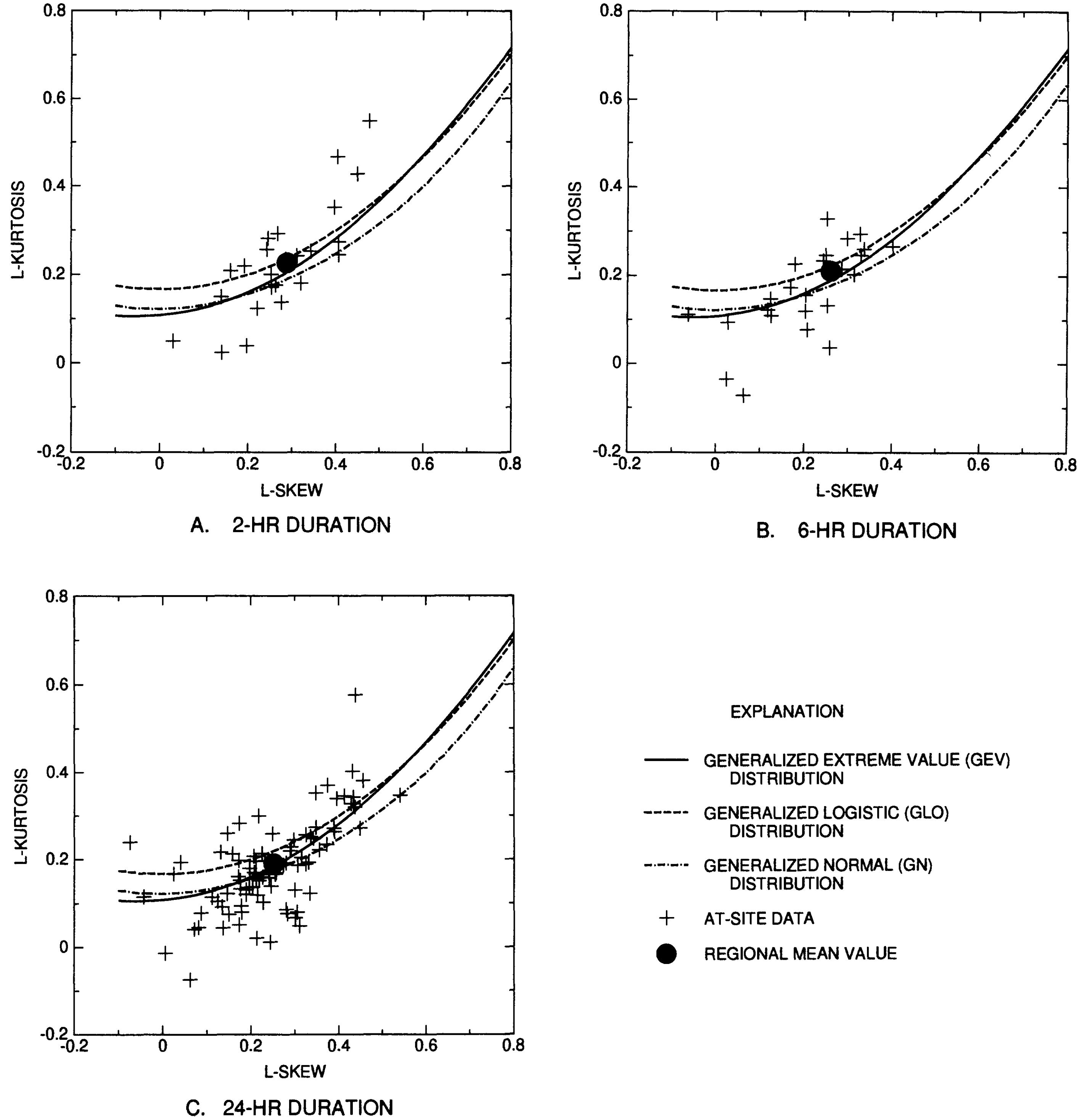

Figure 10. *L*-moment ratios for annual precipitation maxima in Region 2, Montana.

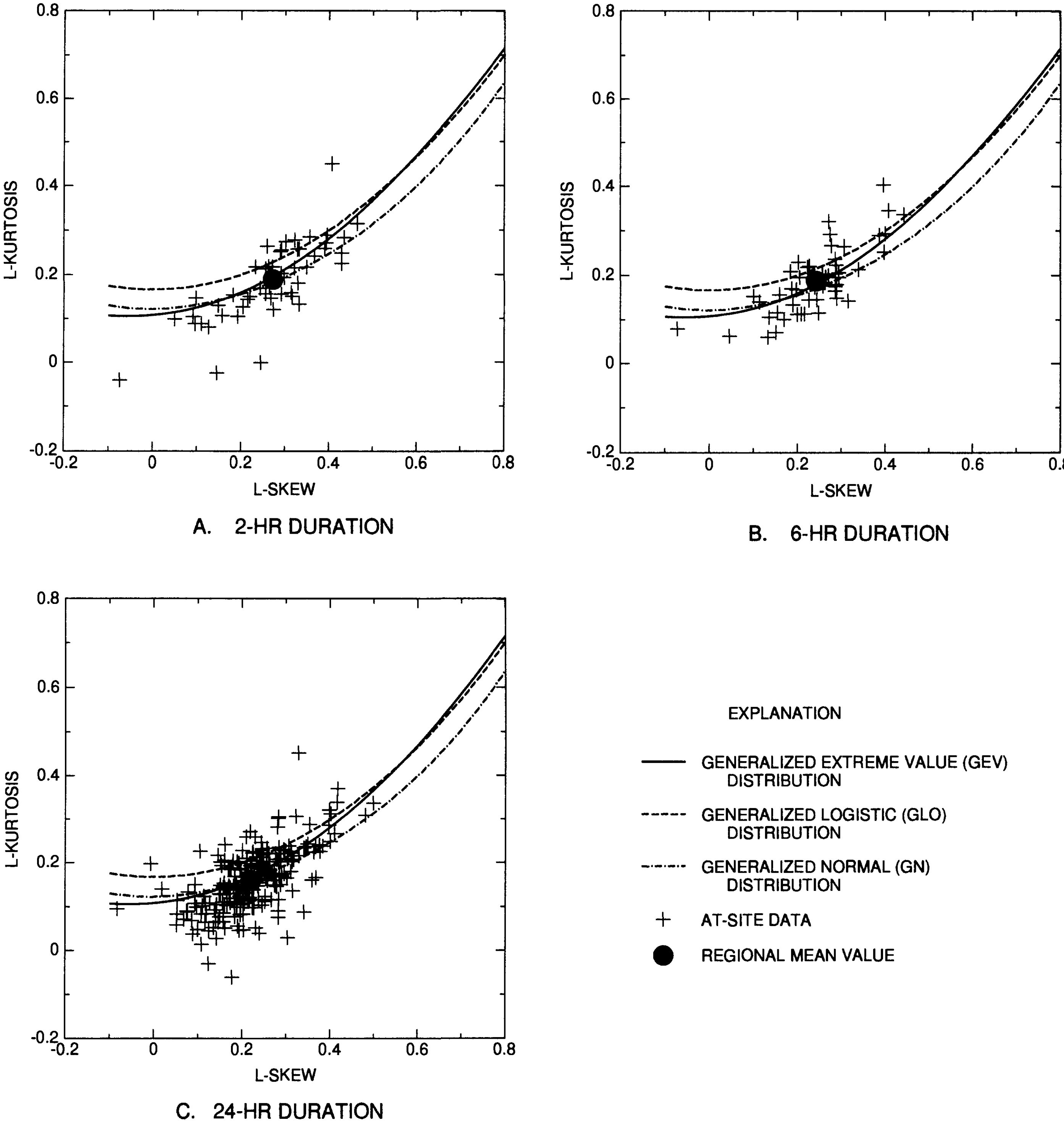

Figure 11. *L*-moment ratios for annual precipitation maxima in Region 3, Montana.

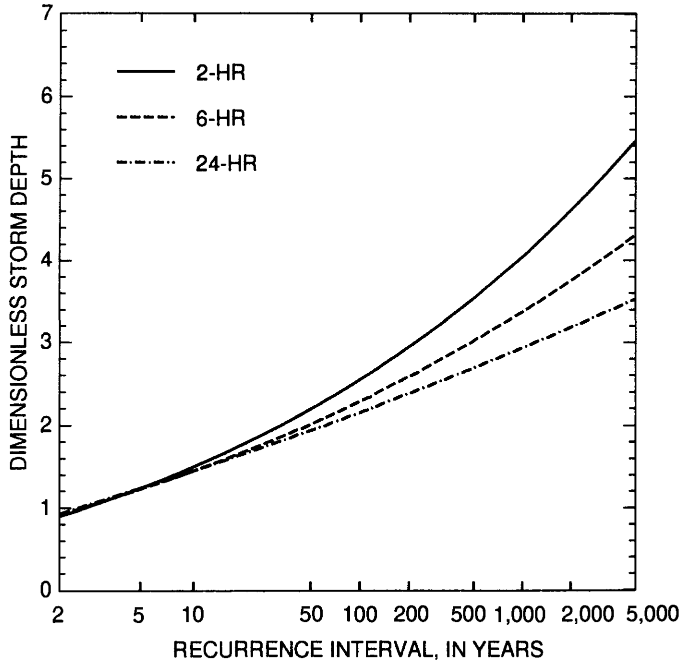

Figure 12. Regional frequency curves for dimensionless annual storm depths in Region 1, Montana.

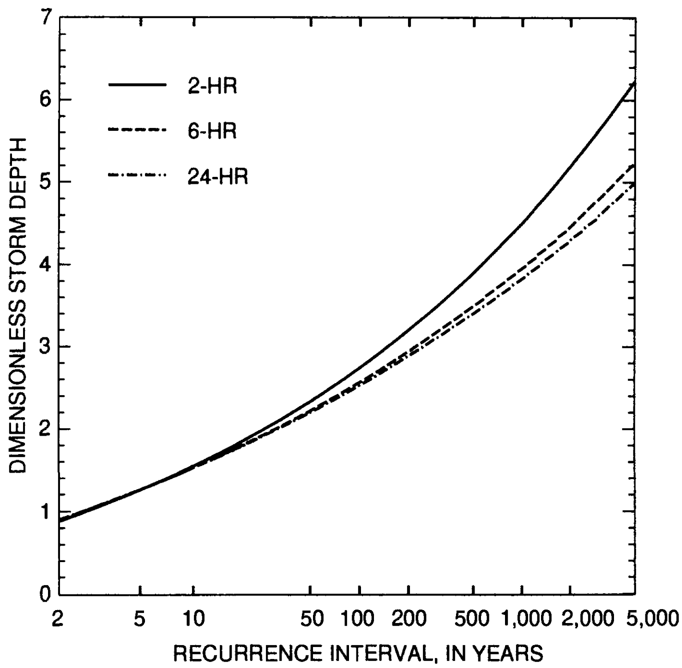

Figure 13. Regional frequency curves for dimensionless annual storm depths for Region 2, Montana.

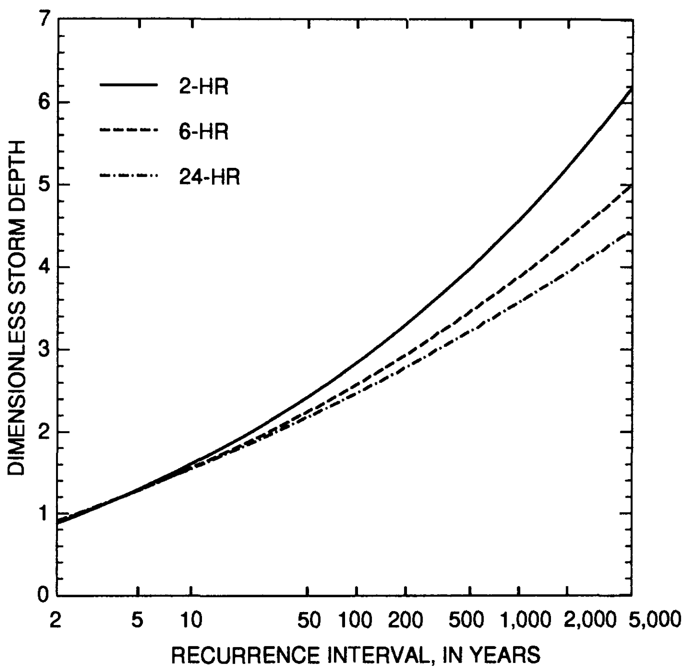

Figure 14. Regional frequency curves for dimensionless annual storm depths for Region 3, Montana.

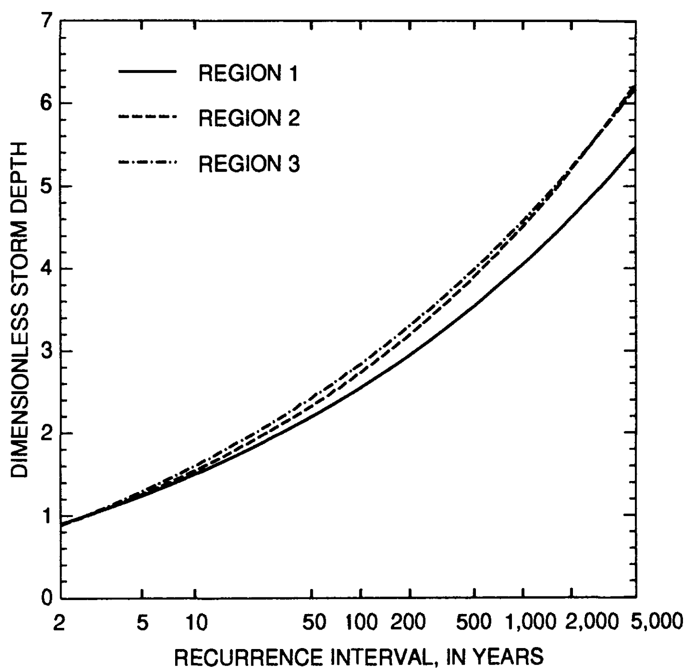

Figure 15. Regional frequency curves for dimensionless 2-hour duration annual precipitation depth, Montana.

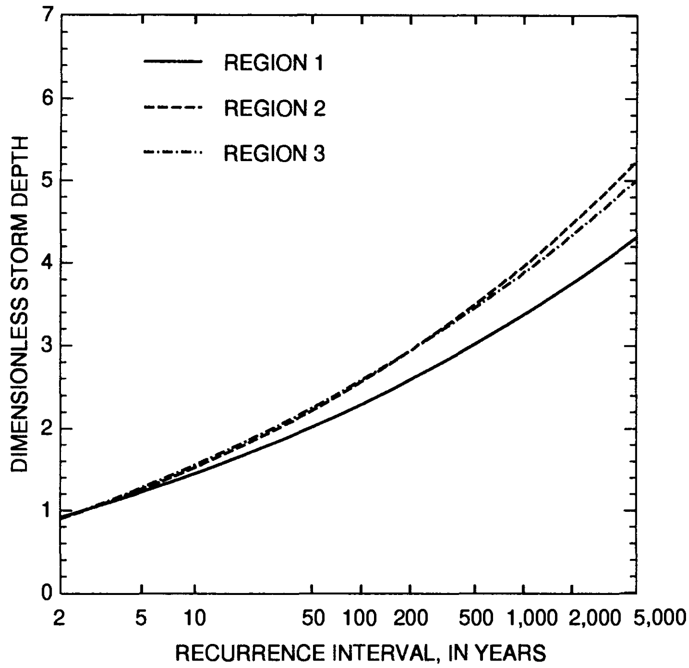

Figure 16. Regional frequency curves for dimensionless 6-hour duration annual precipitation depth, Montana.

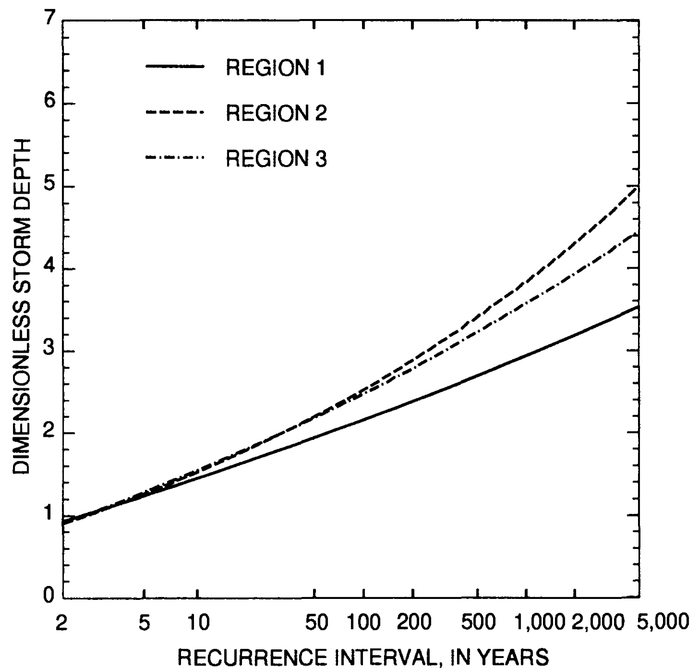

Figure 17. Regional frequency curves for dimensionless 24-hour duration annual precipitation depth, Montana.

For recurrence intervals greater than about 10 years, figures 12-14 indicate that the regional dimensionless frequency curves for 2-hour durations are steeper than those for either 6-hour or 24-hour durations in all regions. Similarly, for recurrence intervals greater than about 50 years, the regional dimensionless frequency curves for 6-hour durations are steeper than those for 24-hour durations. Steeper curves for shorter durations is a natural consequence of the behavior of the regional *L*-moments, which tend to decrease with increasing duration. In particular, the relatively larger *L*-moments and the steeper regional curves for 2-hour durations are likely due to the greater effect of thunderstorms, which tend to be more severe and localized than long-duration general storms.

The reader needs to keep in mind that steeper dimensionless frequency curves for shorter durations do not mean that calculated at-site storm depths are greater for the shorter durations. A value of dimensionless depth obtained from a dimensionless frequency curve needs to be multiplied by an at-site mean value of storm depth to obtain an at-site storm depth for some specified return period. At-site mean depth increases with increasing duration, so a calculated storm depth for any recurrence interval will also increase, although at a lesser rate than the mean, with increasing duration.

Figures 15 and 16 indicate that the dimensionless frequency curves for 2- and 6-hour durations are similar for Regions 2 and 3 and are steeper than those for Region 1. Figure 17 shows that the dimensionless frequency curves for the 24-hour duration are distinctly different for all regions with Region 2 having the largest dimensionless regional quantiles and Region 1 having the smallest. Although Regions 1 and 2 generally are both mountainous, their dimensionless frequency curves are substantially different for all durations. The substantial differences between dimensionless 24-hour duration curves in Regions 1 and 2 are presumed to be largely the result of large, general storms from the Gulf of Mexico that commonly affect the eastern portions of the Rocky Mountains in Montana but only rarely the western portions. Although the plains area of eastern Montana (Region 3) is also affected by storms arising in the Gulf, the lack of mountains and their orographic effect apparently results in generally less severe 24-hour duration storms than in the more mountainous Region 2. The similarity between frequency curves for 2- and 6-hour duration data in Regions 2 and 3 indicates that orographic differences between Regions 2 and 3 do not affect short-duration storms as much as they do long-duration, general storms.

Determination of Effective Regional Record Length

Frequency curves developed from at-site data commonly are used to estimate the magnitude of rare events for which the recurrence intervals are greater than the periods of at-site record. The greater the extrapolation beyond the period of record, the less reliable is the frequency-curve estimate. As reported by Schaefer (1990), a common rule of thumb in conventional at-site frequency analysis is to not exceed about twice the record length when making an estimate of a *T-year* event. For example, if a frequency curve is based on 50 years of at-site record, the rule of thumb indicates that the curve not be used to estimate events having greater than a 100-year recurrence interval.

For a regional analysis wherein all at-site data are combined, an analagous rule of thumb might be to not exceed twice the total station-years of record for all stations used in the analysis. Because of interstation correlation among sites, however, the equivalent regional record length is less than the total station-years of record. In order to estimate a reasonable equivalent regional record length for purposes of evaluating the reliability of regional frequency curves, a graphical method developed by Schaefer (1990) was used. Within each region, annual maxima for each duration were divided by the at-site mean and ranked from largest to smallest. The resultant dimensionless maxima that had common dates of occurrence were compared, and only the largest value was retained in the ranked data set. Counting each storm only one time for each duration within a region was an attempt to eliminate the small degree of interstation correlation and thus ensure that the ranked data would be independent.

After elimination of all storms but one having common dates of occurrence, the recurrence intervals of the 40 largest remaining dimensionless maxima for each duration in each region were determined from the appropriate regional frequency curve. Each calculated recurrence interval was plotted against the rank of each maxima. Thus, the largest recurrence interval was plotted against a rank of 1; the second largest recurrence interval was plotted against a rank of 2; and the smallest recurrence interval was plotted against a rank of 40. The resultant plots of rank versus recurrence interval for the recorded data were compared to smooth curves that relate rank to recurrence interval for theoretical, independent data sampled from a probability distribution that can be described by the following plotting position formula:

$$T'-year = \frac{1}{\left(\frac{i-0.4}{N+0.2}\right)}, \qquad (12)$$

where T'-*year* is the recurrence interval for each ranked data value, i is the rank of the data from largest, 1, to smallest, N, and N is the number of years in the data set.

This plotting position formula has been shown to be generally unbiased and applicable for plotting data from 3-parameter probability distributions such as the GEV (Cunnane, 1978). Comparisons between the plots of recurrence interval versus rank for the 40 largest recorded maxima for each duration and curves from equation 12 for 500; 1,000; 2,000; and 5,000 years are shown by region in figure 18.

As indicated by figure 18 the plots of recurrence interval computed from the GEV distribution versus rank generally lie parallel to and between the curves for the theoretical data sets of various sizes. The approximate sample size (effective regional record length) for each plot can be visually interpolated from its location relative to the smooth curves. On that basis, the effective regional record lengths were determined for each duration within each region and are compared to the total station-years of record in table 10. Although the visual interpolations are somewhat arbitrary and approximate, the results shown in table 10 indicate that the method for estimating effective regional record length is reasonable. For example, table 10 shows that the effective regional record lengths for all durations and regions are less than the total station-years of record. Also, table 10 indicates that the differences between effective regional record lengths and total station-years of record are greatest for 24-hour duration data in all regions and least for 2-hour duration data in all regions. Given that interstation correlation was shown to be greatest for 24-hour duration storm depths and least for 2-hour duration storm depths, the results in table 10 indicate the effects of the interstation correlation. Because the at-site values of precipitation maxima are not completely independent and because the three selected regions had some degree of heterogeneity, a suggested rule of thumb for extrapolation of regional frequency curves for Montana is to not exceed the effective regional record lengths. While this is a heuristic argument and not a statistical one, the rule of thumb appears to be reasonable and supportable by the data given the inherent complexities in the meteorology of extreme storms and the complexity of any rigorous statistical approach. On that basis, the effective regional record lengths shown in table 10 are considered to be reasonable maximum values of recurrence interval for making estimates of at-site annual storm depths in Montana.

Determination of At-Site Mean Storm Depths

As previously discussed, the at-site mean value of storm depth is required to estimate at-site storm depth from the dimensionless regional frequency curves. Regression equations for estimating at-site mean values of storm depth for each duration were developed for each region based on data at all sites used in the regionalization. Explanatory variables considered for use in the regressions were at-site latitude, longitude, mean annual precipitation, and elevation. These variables were selected because they (1) were available at all gaged sites used in the regionalization, and (2) can be fairly easily determined at ungaged sites from topographic maps and maps of mean annual precipitation recently prepared for Montana from digital data compiled by the Oregon State University Climate Center (George Taylor, unpub. data, 1995) (pl. 2).

A regression routine that used all possible combinations of explanatory variables was used, and the "best" model for each duration was considered to be the one that resulted in the minimum value of Mallows' Cp (Helsel and Hirsch, 1992, p. 312-313). Residual plots were also examined to ensure that residuals generally (1) were normally distributed, (2) had constant variance throughout the range of mean precipitation maxima, and (3) were linear. The "best" equation for each duration and two statistics indicating relative regression reliability, standard error of estimate and coefficient of determination (R^2), are shown in table 11. At-site elevation was not a significant explanatory variable for any duration within any region, presumably because it was highly correlated with mean annual precipitation.

As indicated in table 11, the regression equations for 2- and 6-hour duration mean storm depths had smaller standard errors than did the equation for 24-hour duration mean storm depth. The difference may be partly due to the inclusion of SNOTEL sites in the 24-hour duration database, but not in the 2- or 6-hour duration database.

As a test of the overall reliability of the regression equations, 20 precipitation stations were randomly selected from each of the 3 regions of the State and considered to be ungaged sites for which the regression equations were used to calculate mean values of storm depth for 2- , 6- , and 24-hour durations. Methods for estimating mean values of storm depth described in the National Oceanic and Atmospheric Administration (NOAA) Precipitation-frequency Atlas 2 (Miller and

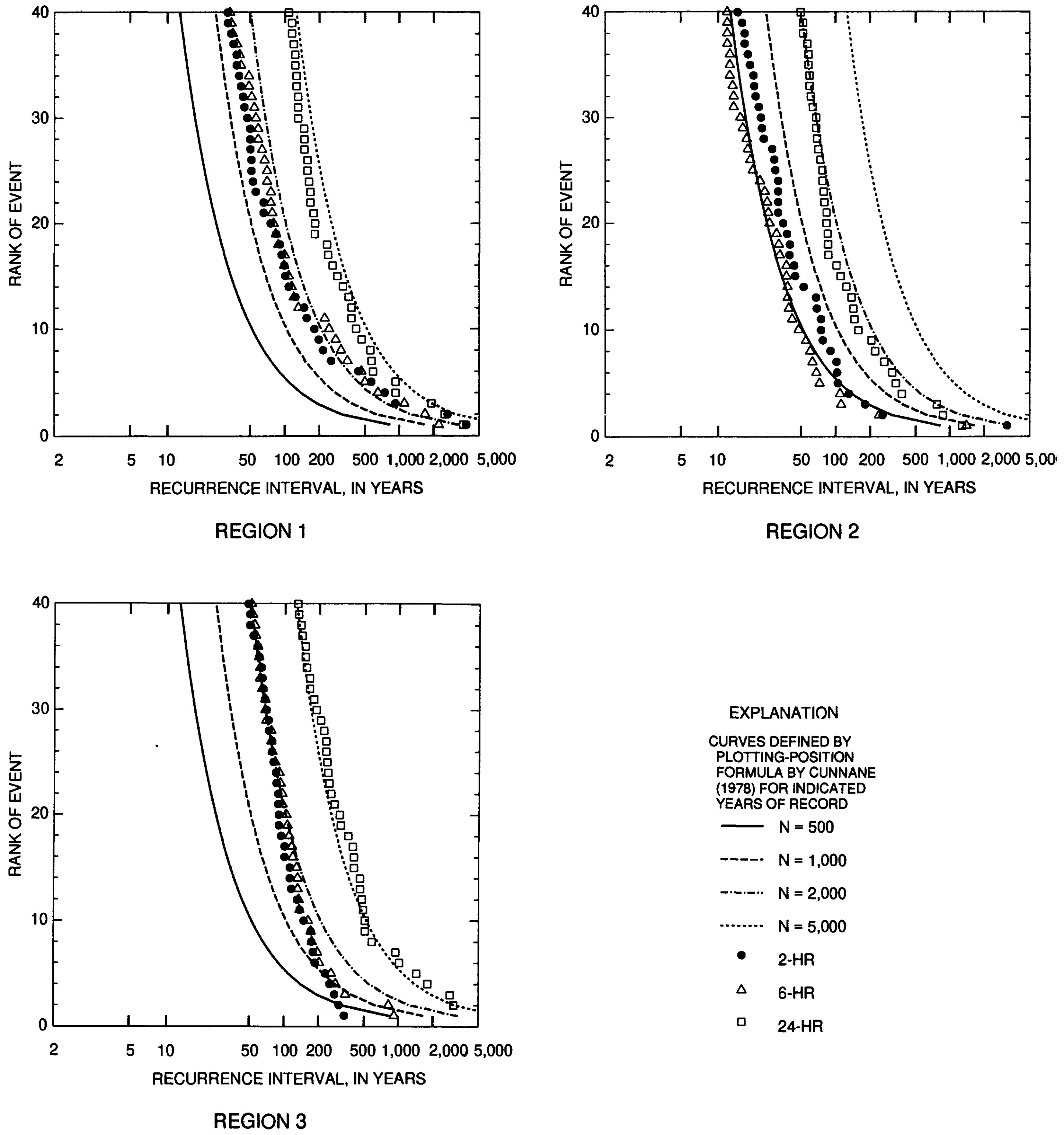

Figure 18. Comparison of scatterplots of rank versus recurrence interval for the 40 largest annual precipitation events with curves for large, independent samples of various sizes, Regions 1, 2, and 3.

Table 10. Total station-years of storm-depth record and effective record length by duration and region, Montana

Duration, in hours	Region	Total station-years of record	Effective record length, in years	Effective record length, in percent of total station-years
2	1	1,375	1,300	95
	2	685	600	88
	3	1,874	1,800	96
6	1	1,574	1,500	95
	2	762	500	66
	3	2,185	1,900	87
24	1	5,593	4,000	72
	2	2,906	1,900	65
	3	10,014	5,100	51

Table 11. Regression equations for estimation of mean storm depth for indicated duration in Montana

[Regression equation: *Pmaxt*, storm depth in inches, with t indicating duration in hours; *LAT*, site latitude, in decimal degrees minus 40; *LONG*, site longitude, in decimal degrees minus 100; and *MAP*, mean annual precipitation, in inches, as determined from State maps prepared from digital data from Oregon State University Climate Center (pl. 2)]

Region	Equation	Standard error, inches	Coefficient of determination, R^2
1	$Pmax2 = 0.44 + (0.0027 \times MAP)$	0.05	0.10
	$Pmax6 = 0.60 + (0.0067 \times MAP)$	0.07	0.31
	$Pmax24 = 1.0 + (0.078 \times LAT) - (0.059 \times LONG) + (0.025 \times MAP)$	0.16	0.80
2	$Pmax2 = 0.69 + (0.034 \times LAT) - (0.029 \times LONG)$	0.09	0.16
	$Pmax6 = 0.75 + (0.087 \times LAT) - (0.041 \times LONG)$	0.12	0.30
	$Pmax24 = 1.4 + (0.18 \times LAT) - (0.13 \times LONG) + (0.019 \times MAP)$	0.27	0.52
3	$Pmax2 = 0.70 + (0.031 \times LAT) - (0.040 \times LONG) + (0.0087 \times MAP)$	0.08	0.62
	$Pmax6 = 0.85 + (0.031 \times LAT) - (0.038 \times LONG) + (0.015 \times MAP)$	0.08	0.59
	$Pmax24 = 0.62 + (0.039 \times LAT) - (0.016 \times LONG) + (0.058 \times MAP)$	0.16	0.49

others, 1973) were also used to calculate mean values of storm depth for the same durations at the same 20 test sites. Results from the regression equations and from the methods described in NOAA Atlas 2 were compared to actual values of mean storm depth determined from the gaged record, and the standard deviation of the differences (residuals) between calculated and actual values are shown in table 12. As shown in table 12, the results from the regression equations generally had lower standard deviations of residuals than did the results from the methods described in NOAA Atlas 2. Accordingly, the regression equations are considered to be generally more reliable within Montana than the methods described in NOAA Atlas 2.

Table 12. Results of comparison test between regression equations and methods in NOAA Atlas 2, volume 1, Montana[1]

Duration, hours	Standard deviation of residuals for estimates of mean storm depth from regression equations, inches	Standard deviation of residuals for estimates of mean storm depth made using NOAA Atlas 2, inches
2	0.05	0.09
6	.08	.11
24	.15	.20

[1]Miller and others, 1973.

An alternative method for the estimation of an at-site mean value of storm depth is to use the mean storm depth obtained from recorded data at a nearby station. If the station is relatively close to the ungaged site and has a similar elevation, the mean storm depth at the station is likely to be similar to that at the ungaged site and, perhaps, a better estimate of mean storm depth at the ungaged site than that from a regression equation.

To test whether estimates from nearby stations could be considered to be as reliable as estimates from regression equations, the nearest station having data for the same storm duration to each of the 20 test stations was used to estimate mean storm depth for 2-, 6-, and 24-hour durations at each test station. The standard deviation of differences (residuals) in mean storm depth was calculated for the 20 pairs of stations. The standard deviation of differences for each duration is shown in table 13, together with the mean values of interstation distance and elevation difference for the 20 pairs of stations. The standard deviations shown in table 13 generally are the same or smaller than the standard deviations of differences for the regression equations and for the methods of NOAA Atlas 2 (table 12). On that basis, the use of a nearby station to estimate mean storm depth at an ungaged site is considered to be at least as reliable as the use of regression equations so long as the interstation distance and elevation difference between the nearby station and the site of interest are not substantially greater than the mean values in table 13.

Table 13. Standard deviation of residuals and mean values of interstation distance and elevation difference for use of nearby station to estimate mean storm depth, Montana

Duration, hours	Standard deviation of residuals for estimates of mean storm depth using nearby stations, inches	Mean interstation distance, miles	Mean elevation difference, feet
2	0.05	24.3	707
6	.06	23.3	712
24	.11	10.4	358

Depth-Area Adjustment Curves

For most rainfall-runoff applications, a basin-average value of storm depth is required rather than an at-site or point value. For any given storm, precipitation depth varies spatially from the storm center, or point of maximum depth, to the storm edges where precipitation depth is zero. Thus, for storms centered on a basin, the basin-average value of storm depth will always be less than the value at the basin or storm center. The degree to which point estimates of precipitation depth need to be adjusted downward to yield basin-average values depends upon basin size and storm duration. Storms that are large in areal extent will completely cover small basins so that little or no downward adjustment of point values of precipitation depth is required for small basins. Storms that are large in areal extent also generally have longer durations, so the degree of downward adjustment of point values to basin-average values generally decreases with increasing storm duration.

Adjustments to point values of precipitation depth to produce basin-average values commonly are made through the use of depth-area adjustment curves. Although the determination of depth-area adjustment curves for Montana was beyond the scope of the current study, various depth-area adjustment curves have been developed for other studies (Hansen and others, 1988; Miller and others, 1973; U.S. Weather Bureau, 1981; U.S. Department of Agriculture, 1972). The variation among these published depth-area adjustment curves is fairly large, especially for short-duration

(2-hour) storms and large basins (drainage areas greater than about 100 square miles). Of these published depth-area adjustment curves, those developed by Miller and others (1973) result in the smallest reduction of point precipitation depths and thus are considered to be the most conservative. For most dam-safety and design applications, the depth-area adjustment curves by Miller and others (1973) thus are considered to be most applicable and are included here for easy reference (fig. 19).

Estimation of a basin-average storm depth for a specified recurrence interval generally requires that several estimates of at-site storm depth be averaged. The number of at-site estimates required to provide a reasonable basin-average value depends upon the areal variation in mean at-site storm depth as determined by equations in table 11. In relatively small basins in eastern Montana where mean annual precipitation does not have much variation, calculated mean at-site storm depth also will not have much variation. For these basins, a single at-site estimate of storm depth at the basin centroid can be used with the appropriate curve in figure 19 to estimate basin-average storm depth. For larger basins in eastern Montana and for most basins in the mountains of Region 1 and 2 where mean annual precipitation varies substantially, several at-site estimates of storm depth are required. A grid-sampling method can be used for these basins to uniformly select points for at-site calculation of mean storm depth. To apply the grid-sampling method, a transparent grid is overlaid on a map of the basin, and a calculation of at-site mean storm depth is made for each grid intersection within the basin boundary. For each calculated mean storm depth, the appropriate dimensionless precipitation-frequency curve is used to calculate at-site storm depth for the specified recurrence interval, and all estimates of at-site storm depth are averaged. The areally averaged value of at-site storm depth is then used with the appropriate depth-area curve in figure 19 to estimate basin-average storm depth.

Application of Regional Analysis Approach and Limitations

Determination of an at-site storm depth for a selected recurrence interval and storm duration requires an estimate of at-site mean storm depth for the selected duration and application of one of the three dimensionless precipitation frequency curves (figures 12-14 or figures 15-17). Selection of an appropriate storm duration and recurrence interval depends upon the problem under consideration and is beyond the

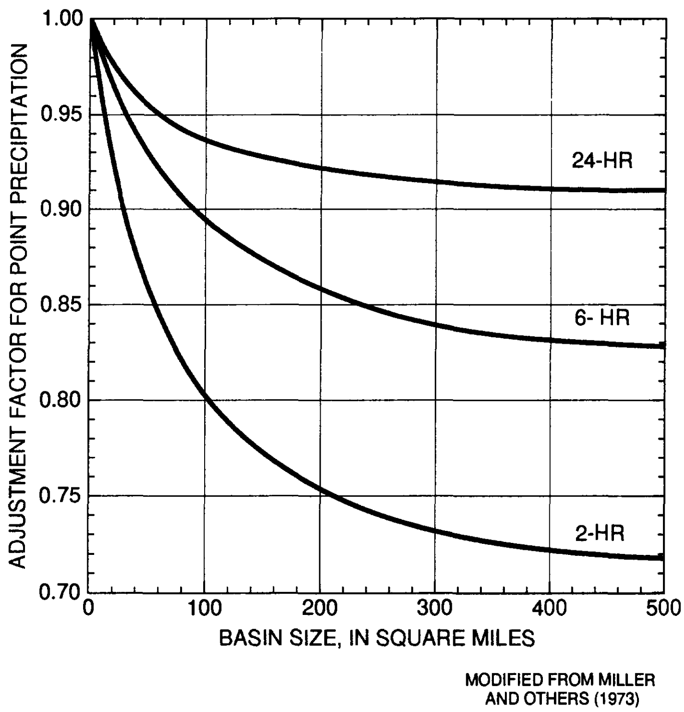

Figure 19. Depth-area adjustment curves for Montana.

scope of this report. For rainfall-runoff determinations, storm duration generally is a function of the size of watershed under consideration and needs to be sufficiently long to ensure that the maximum rate of runoff results from the total depth of precipitation. In addition, depending upon the storage capacity of a reservoir relative to the runoff-generating capability of the watershed, total runoff volume from a storm may, in some instances, be more important than the maximum rate of runoff. If so, the appropriate storm duration will likely be longer than that required to produce the maximum rate of runoff. Given these considerations, an appropriate minimum storm duration is related to the time of travel of runoff from the farthest point in the basin to the point of interest and can be calculated from the physical characteristics of the basin (Holnbeck and Parrett, 1996). Selection of an appropriate recurrence interval for a rainfall-runoff problem relates to the risk of failure, and what constitutes an acceptable level of risk needs to be determined administratively. In general terms, the greater the risk to life or property, the greater the recurrence level needs to be.

The following examples are intended to illustrate the methods for estimation of annual precipitation maxima for typical dam-safety applications in Montana where storm duration and recurrence interval previously have been determined. The examples require some hydrologic judgment about: (1) the relation between recurrence interval of a storm and recurrence interval of the resultant runoff, (2) the use of precipitation-frequency curves for sites near regional boundaries, (3) application of the grid-sampling method for estimation of at-site storm depths, or (4) the use of alternative methods for estimation of mean values of storm depth. Discussion about the degree of judgment required and its effect on the reliability of the estimates is provided for each example. The choices made in the examples are intended to be reasonable and are not necessarily the same choices that would be made for actual design applications where larger, more conservative, or smaller, less conservative, estimates might be required.

Example 1:

An estimate of an at-site precipitation depth for a 6-hour duration storm is required for a location at the centroid of a small, 5-square mile basin in southwestern Montana. The site latitude is 45°, and the site longitude is 112°30'. The estimate will be used in a rainfall-runoff model where the required recurrence interval of the runoff is 100 years. Average conditions of basin infiltration are assumed, so the recurrence interval of the precipitation maximum is assumed to be the same as that for the runoff (100 years).

Solution:

Based on the latitude and longitude, the site is determined to be in Region 1. The dimensionless storm depth for a 6-hour duration storm having a 100-year recurrence interval is determined from figure 12 to be 2.3. From the map of mean annual precipitation (pl. 2), the mean annual precipitation for the site is determined to be 18 inches. The at-site mean 6-hour storm depth is calculated from the equation for *Pmax6* in table 11 as follows:

$$\begin{aligned} Pmax6 &= 0.60 + (0.0067 \times MAP) \\ &= 0.60 + (0.0067 \times 18) \\ &= 0.60 + 0.12 \\ &= 0.72 \text{ inches} \end{aligned}$$

Multiplying the dimensionless storm depth times the at-site mean storm depth yields the following estimate of precipitation depth for a 6-hour duration storm having a 100-year recurrence interval:

$$\begin{aligned} Depth &= 2.3 \times 0.72 \\ &= 1.7 \text{ inches.} \end{aligned}$$

Discussion:

The assumption that recurrence interval of the storm is equivalent to recurrence interval of the runoff is commonly made. Readers need to be aware, however, that the rainfall-runoff process is very complex, and that a storm depth having a given recurrence interval can produce runoff having a wide range in recurrence intervals depending upon the location, uniformity, and temporal characteristics of the storm and hydrologic conditions in the basin. For example, a storm having a small recurrence interval can produce runoff having a large recurrence interval if basin infiltration is abnormally small. In a very general sense, if storm characteristics and hydrologic conditions in a basin are typical for the season (average values), it seems reasonable to assume that recurrence intervals for storm depth and runoff are similar.

Because the site is not located close to a regional boundary and because the recurrence interval is much less than the equivalent record length of 1,500 years, no adjustments to the estimated storm depth or conditions on its use are considered necessary.

Example 2:

A basin-average estimate of precipitation depth for a 24-hour duration storm is required for spillway modification on a reservoir having a 150-square mile drainage basin in Central Montana. Because the basin is relatively large and varies in elevation, the grid-sampling method is used to select five grid intersections for the calculation of at-site storm depths. The latitudes of the five grid intersections range from 46°45' to 46°55' and the longitudes of the five grid intersections range from 109°45' to 109°55'. The site is considered to be a relatively high-risk site, and the required recurrence interval for the 24-hour duration storm-depth estimate is selected to be 2,000 years.

Solution:

From the given latitudes and longitudes, the basin is determined from plate 1 to be partly in Region 2 and partly in Region 3. Three of the grid intersections where at-site storm depth is to be calculated are determined to be in Region 2, and two are determined to be in Region 3. From figure 17, values of dimensionless precipitation depth for a 24-hour storm having a 2,000 year recurrence interval are found to be 4.3 in Region 2 and 3.9 in Region 3.

From plate 2, the mean annual precipitation at the 5 grid intersections ranges from 14 to 30 inches. The at-site mean precipitation depth for a 24-hour storm is calculated for each grid intersection using the equations for *Pmax*24 in table 11. The results of the calculations are shown below:

Region	*Pmax*24, in inches
2	1.9
2	1.8
2	1.7
3	1.7
3	1.5

Storm depths for the three grid intersections in Region 2 are calculated by multiplying each value of *Pmax*24 by the dimensionless precipitation depth, 4.3, as follows:

Depth (1) = 4.3 x 1.9 = 8.2 inches
Depth (2) = 4.3 x 1.8 = 7.7 inches
Depth (3) = 4.3 x 1.7 = 7.3 inches

Likewise, storm depths for the two grid intersections in Region 3 are calculated by multiplying each value of *Pmax*24 by the dimensionless precipitation depth, 3.9, as follows:

Depth (4) = 3.9 x 1.5 = 5.9 inches
Depth (5) = 3.9 x 1.7 = 6.6 inches

The five calculated at-site storm depths are averaged to obtain a value of 7.1 inches. From the depth-area curve for 24-hour duration storms in figure 19, the depth-area adjustment factor for a 150-square mile basin is found to be 0.93. Finally, multiplication of the depth-area adjustment factor by the average at-site storm depth yields the basin-average precipitation depth for a 2,000-year, 24-hour duration storm as:

Basin-average depth = 0.93 x 7.1 inches
= 6.6 inches

Discussion:

Although the recurrence interval of 2,000 years is large, it is less than the equivalent record length for 24-hour duration data in Region 3 (5,100 years) and only slightly greater than the equivalent record length for 24-hour duration data in Region 2 (1,900 years). The basin-average estimate based on the at-site estimates for Regions 2 and 3 is thus considered to meet the suggested rule of thumb for extrapolation of regional precipitation-frequency curves for Montana and to be a reasonable estimate.

Because the location of regional boundaries is somewhat arbitrary, an alternative approach for this problem would be to use only the dimensionless precipitation-frequency curve for Region 2 rather than curves for both Regions 2 and 3. The calculated at-site precipitation depths at the two grid intersections in Region 3 would then be as follows:

Depth (4) = 4.3 x 1.7 = 7.3 inches
Depth (5) = 4.3 x 1.5 = 6.5 inches

The average value of at-site precipitation depth would be 7.4 inches, and the basin-average storm depth would be:

Basin-average depth = 0.93 x 7.4
= 6.9 inches

Given the large recurrence interval required, the alternative approach, which provides a conservatively larger storm depth, might be more appropriate for this example.

Example 3:

Estimates of storm depths for 2-,6-, and 24-hour durations are required for design of a flood-control structure on a small, 3.5 square mile basin in the mountains of western Montana (Region 1). The latitude and longitude of the basin outlet are 47°11' and 113°18', respectively. The mean annual precipitation at this site is determined from plate 2 to be 40 inches. An appropriate recurrence interval for design has not been determined, so a precipitation frequency curve will be determined for each duration. A long-term precipitation station is located about 3 miles south of the basin at an elevation about 100 feet lower than the basin outlet. The mean storm depths for durations of 2-, 6-, and 24-hours at the station are 0.70, 1.0, and 1.9 inches, respectively.

Solution:

Because of the small size of the basin, a single at-site estimate of precipitation depth at the basin outlet is considered to be representative of average precipitation over the basin.

Using the equations for *Pmax*2, *Pmax*6, and *Pmax*24 for Region 1 in Table 11 to calculate at-site mean storm depth gives the following:

*Pmax*2 = 0.44 + (0.0027 x 40)
= 0.44 + 0.11
= 0.55 inch
*Pmax*6 = 0.60 + (0.0067 x 40)
= 0.60 + 0.27
= 0.87 inch
*Pmax*24 = 1.0 + (0.078 x 7.2) - (0.059 x 13) + (0.025 x 40)
= 1.0 + 0.56 - 0.77 + 1.0
= 1.8 inch

Because the nearby precipitation station is considered to be meteorologically similar to the basin outlet, the slightly larger mean storm depths at the nearby station are used to calculate storm depths from the dimensionless precipitation frequency curves rather than the mean depths obtained from the regression equations.

From figure 12, ordinates for various recurrence intervals for each duration were selected to produce table 14.

The columns of dimensionless storm depths in table 14 were each multiplied by the mean storm depth for the appropriate duration to produce table 15 for plotting storm depth frequency curves. Equations 3 and 4 were used to convert the *T-year* recurrence interval in table 15 to GRV for plotting purposes as previously described, and the final storm-depth frequency curves for the example site are shown in figure 20. Data in tables 14 and 15 are all shown to two decimal places to ensure that the final storm-depth frequency curves would be relatively smooth.

Discussion:

Figure 20 indicates that, as expected, at-site storm depths increase with increasing duration for any given recurrence interval. As was previously discussed, this result may not have been evident from the dimensionless precipitation frequency curves in figures 12-14.

Table 14. Dimensionless storm depths for indicated durations and recurrence intervals for hypothetical site in Region 1, Montana

Recurrence interval (years)	Dimensionless storm depth for indicated duration		
	2-hour	6-hour	24-hour
2	0.90	0.90	0.90
5	1.25	1.25	1.25
10	1.50	1.45	1.45
50	2.20	2.05	1.95
100	2.55	2.30	2.15
200	2.95	2.60	2.40
500	3.55	3.00	2.70
1,000	4.05	3.40	2.95
2,000	4.65	3.80	3.20
5,000	5.45	4.30	3.52

Table 15. Storm depths for indicated durations and recurrence intervals for hypothetical site in Region 1, Montana

Recurrence interval (years)	Storm depth (in inches) for indicated duration		
	2-hour	6-hour	24-hour
2	0.63	0.90	1.71
5	0.88	1.25	2.38
10	1.05	1.45	2.76
50	1.54	2.05	3.70
100	1.78	2.30	4.08
200	2.06	2.60	4.56
500	2.48	3.00	5.13
1,000	2.84	3.40	5.60
2,000	3.26	3.80	6.08
5,000	3.82	4.30	6.69

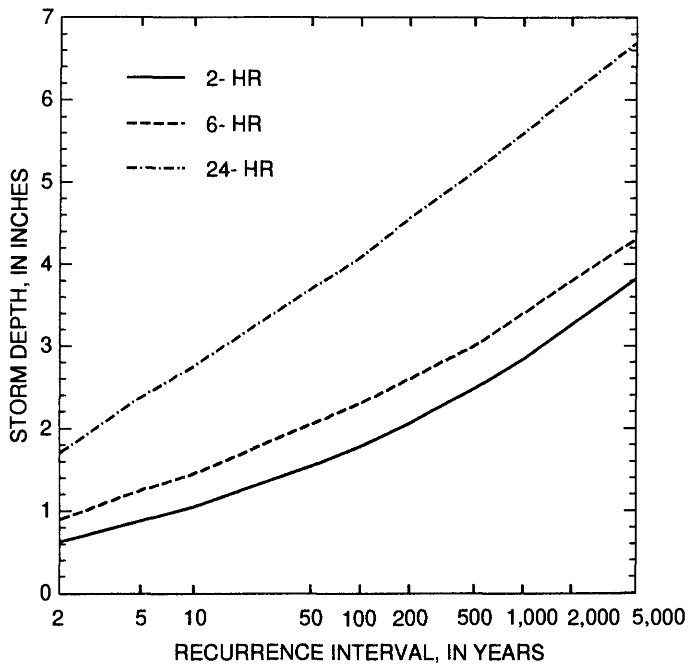

Figure 20. Storm-depth frequency curves for hypothetical site in Region 1, Montana.

The dimensionless curves generally increase in steepness and have larger ordinates as the durations decrease. On that basis, the dimensionless curves seem to imply that calculated at-site storm depths for a given recurrence interval might be larger for short durations than for long durations. As the results in example 3 indicate, scaling the dimensionless ordinates by the mean storm depth removes the anomalous appearance of the dimensionless frequency curves and results in at-site storm-depth frequency curves that are reasonable.

SUMMARY

Methods for estimating precipitation depths based on probability of exceedance are required to better evaluate risk of dam failure and establish a more consistent basis for spillway design. A regional analysis of annual precipitation maxima for Montana resulted in dimensionless precipitation-frequency curves for 2-, 6-, and 24-hour storm durations for three acceptably homogeneous regions in Montana. Within each homogeneous region, at-site annual precipitation maxima were made dimensionless by dividing by the at-site mean and pooled for analysis to yield a single dimensionless frequency curve applicable for each duration. *L*-moment statistics were used to help define the homogeneous regions and to develop the dimensionless precipitation-frequency curves.

Data from 122 hourly and 283 daily precipitation stations operated by the National Weather Service and 54 daily precipitation stations operated by the Natural Resources Conservation Service were used to develop the database of annual precipitation maxima. Four hourly and 22 daily sites were located in northern Wyoming. All stations had at least 10 years of data. Because of periods of missing data, precipitation data were carefully scrutinized to ensure that reported annual maxima were true maxima. Data were tested to ensure that 24-hour duration maxima from the daily stations were, after application of an adjustment factor, equivalent to 24-hour duration maxima determined from hourly stations. Data were also tested to ensure that annual maxima based on different annual periods were equivalent. Statistical tests were applied to the annual precipitation maxima to ensure that the data were not serially correlated and were stationary over the general period of data collection (1900-92). The data also were tested for spatial independence using the interstation correlation coefficient and found to have a small, but significant, degree of interstation correlation.

Several attempts were made to delineate homogeneous regions. The first attempt, based on a previous study in Washington State, delineated regions such that each had a small range in values of mean annual precipitation. Results of a statistical test for regional heterogeneity based on *L*-moments indicated that regions delineated on the basis of a small range in values of mean annual precipitation generally were not homogeneous in Montana. A second attempt delineated regions such that each had a small range in values of site elevation. This attempt also generally resulted in non-homogeneous regions based on results of the heterogeneity test. Three regions previously delineated on the basis of physiography and climate also were tested and found to be acceptably homogeneous for purposes of this study. One region (Region 1) consisted of generally mountainous western Montana where large storms generally receive their moisture from the Pacific Ocean. A second region (Region 2) included the mountains forming the eastern edge of the Rocky Mountain range where large storms are often the result of the orographic uplifting of moisture systems originating in the Gulf of Mexico. The third region (Region 3) consisted of the plains areas of eastern Montana where large storms may originate from moisture sources in the Pacific Ocean or the Gulf of Mexico. Although the three regions did not meet the statistical test for homogeneity based on *L*-moments for all storm durations, the same regional boundaries were used for all storm durations to define acceptably "homogeneous" regions.

Within each homogeneous region, regional values of *L*-moments and *L*-moment ratios were used to calculate parameters of several candidate probability distributions. A goodness-of-fit test was used to help select an acceptable distribution for each duration within each region. The distribution that most often satisfied the goodness-of-fit test and was thus selected as the best distribution for all durations and regions was the 3-parameter Generalized Extreme Value (GEV) distribution. The GEV distribution was used to construct dimensionless frequency curves of annual storm depth for each duration within each region. Each dimensionless frequency curve was considered to be reliable for recurrence intervals up to the effective record length. Because of significant, though small, interstation correlation in all regions for all durations, and because the selected regions exhibited some heterogeneity, the effective record length was considered to be less than the total number of station-years of data. The effective record length for each duration in each region was estimated using a graphical method and found to range from 500 years for 6-hour duration data in Region 2 to 5,100 years for 24-hour duration data in Region 3.

Because the dimensionless frequency curves are scaled by the mean values of annual storm depth, using the curves to estimate precipitation depths for specified durations and exceedance probabilities at ungaged sites requires the estimation of mean storm depths for the specified durations. Regression equations for the estimation of mean storm depths for durations of 2, 6, and 24 hours were developed. Explanatory variables for the regression equations included site location (latitude and longitude) and mean annual precipitation. The regression equations were tested against methods for estimating mean values previously developed by the National Weather Service and were determined to be generally more reliable within Montana than the previously developed methods. Use of a nearby precipitation station to estimate mean storm depths at an ungaged site also was tested and found to be at least as reliable as use of a regression equation.

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Table 1. Precipitation stations, Montana and northern Wyoming, and pertinent station information

[All stations located in Montana, except those with numbers starting with "48," which are located in Wyoming. Agency: NRCS, Natural Resources Conservation Service; NWS, National Weather Service. Type of gage: Daily, precipitation gage that records daily totals; Hourly, precipitation gage that records hourly totals. Symbol: --, no data]

Station no.	Name	Latitude, in decimal degrees	Longitude, in decimal degrees	Mean annual precipitation, in inches	Period of station record used in analysis		Elevation, in feet above sea level	Agency	Type of gage	Mean storm depth, in inches, for indicated duration, in hours		
					Begin date	End date				2	6	24
09C01S	Crystal Lake	46.7833	109.5000	38.4	1980	1992	6,050	NRCS	Daily	--	--	2.60
09D06S	Fisher Creek	45.0667	109.9500	59.0	1980	1992	9,100	NRCS	Daily	--	--	2.16
09D16S	Cole Creek	45.2000	109.3500	38.9	1980	1992	7,850	NRCS	Daily	--	--	2.64
09D18S	Silver Run	45.1500	109.3500	21.5	1981	1992	6,630	NRCS	Daily	--	--	1.95
10C03S	Porcupine	46.1167	110.4667	27.5	1980	1992	6,500	NRCS	Daily	--	--	1.66
10C06S	Spur Park	46.7833	110.6167	41.5	1980	1992	8,100	NRCS	Daily	--	--	1.57
10C09S	Deadman Creek	46.8000	110.6833	27.6	1980	1992	6,450	NRCS	Daily	--	--	1.51
10D13S	Lick Creek	45.5000	110.9667	34.8	1980	1992	6,860	NRCS	Daily	--	--	1.89
10D16S	Shower Falls	45.4000	110.9500	51.9	1981	1992	8,100	NRCS	Daily	--	--	1.75
10D24S	Placer Basin	45.4167	110.1000	39.8	1981	1992	8,830	NRCS	Daily	--	--	1.79
10D31S	Box Canyon	45.2833	110.2500	26.0	1980	1992	6,700	NRCS	Daily	--	--	1.26
11C01S	Boulder Mountain	46.5667	111.3000	41.8	1980	1992	7,950	NRCS	Daily	--	--	2.11
11C02S	Pickfoot Creek	46.5833	111.2667	31.2	1980	1992	6,650	NRCS	Daily	--	--	1.76
11D08S	Clover Meadow	45.0167	111.8500	36.8	1980	1992	8,800	NRCS	Daily	--	--	1.67
11D11S	Lower Twin	45.5000	111.9167	43.7	1981	1992	7,900	NRCS	Daily	--	--	1.82
11E03S	Lakeview Ridge	44.5833	111.8333	32.4	1980	1992	7,400	NRCS	Daily	--	--	1.86
11E24S	Tepee Creek	44.7833	111.7000	29.8	1980	1992	8,000	NRCS	Daily	--	--	1.67
11E35S	Black Bear	44.5000	111.1167	61.7	1980	1992	8,150	NRCS	Daily	--	--	2.17
12B12S	Mount Lockhart	47.9167	112.8167	44.5	1980	1992	6,400	NRCS	Daily	--	--	2.16
12B13S	Waldron	47.9167	112.7833	31.8	1980	1992	5,600	NRCS	Daily	--	--	2.06
12B14S	Copper Camp	47.0833	112.7333	52.8	1980	1992	6,950	NRCS	Daily	--	--	2.29
12B16S	Copper Bottom	47.0500	112.6000	27.0	1980	1992	5,200	NRCS	Daily	--	--	1.42
12C11S	Rocker Peak	46.3667	112.2500	32.1	1980	1992	8,000	NRCS	Daily	--	--	1.65
12C13S	Frohner Meadow	46.4500	112.2000	25.6	1980	1992	6,480	NRCS	Daily	--	--	1.78
12C21S	Nevada Creek	46.8333	112.5167	31.7	1982	1992	6,480	NRCS	Daily	--	--	1.64
12D09S	Basin Creek	45.8000	112.5167	25.1	1982	1992	7,180	NRCS	Daily	--	--	1.36
12D11S	Mule Creek	45.4000	112.9667	30.9	1981	1992	8,300	NRCS	Daily	--	--	1.52
12E07S	Divide	44.8000	112.0500	27.4	1981	1992	7,800	NRCS	Daily	--	--	1.54
12E08S	Beagle Springs	44.4667	112.9833	25.1	1981	1992	8,850	NRCS	Daily	--	--	1.49
13A15S	Badger Pass	48.1333	113.0167	61.4	1981	1992	6,900	NRCS	Daily	--	--	2.60

Table 1. Precipitation stations, Montana and northern Wyoming, and pertinent station information (Continued)

Station no.	Name	Latitude, in decimal degrees	Longi-tude, in decimal degrees	Mean annual precipita-tion, in inches	Period of station record used in analysis		Elevation, in feet above sea level	Agency	Type of gage	Mean storm depth, in inches, for indicated duration, in hours		
					Begin date	End date				2	6	24
13A19S	Flattop Mountain	48.8000	113.8500	84.0	1980	1992	6,300	NRCS	Daily	--	--	2.69
13A24S	Emery Creek	48.4333	113.9333	39.8	1982	1992	4,350	NRCS	Daily	--	--	1.86
13A25S	Noisy Basin	48.1500	113.9500	76.0	1980	1992	6,040	NRCS	Daily	--	--	2.95
13A26S	Pike Creek	48.3000	113.3333	52.2	1982	1992	5,930	NRCS	Daily	--	--	2.39
13B22S	Kraft Creek	47.4333	113.7667	41.0	1982	1992	4,750	NRCS	Daily	--	--	1.93
13C03S	Skalkaho Summit	46.2500	113.7667	39.1	1981	1992	7,250	NRCS	Daily	--	--	1.47
13C13S	Black Pine	46.4167	113.4333	28.3	1980	1992	7,210	NRCS	Daily	--	--	1.45
13C31S	North Fork Elk Creek	46.8667	113.2667	32.2	1980	1992	6,250	NRCS	Daily	--	--	1.51
13C33S	Combination	46.4667	113.4000	21.4	1980	1992	5,600	NRCS	Daily	--	--	1.25
13C38S	Lubrecht Flume	46.8833	113.3167	23.8	1980	1992	4,680	NRCS	Daily	--	--	1.47
13C39S	Daly Creek	46.1833	113.8500	25.0	1981	1992	5,780	NRCS	Daily	--	--	1.08
13C43S	Warm Springs	46.2667	113.1667	44.5	1982	1992	7,800	NRCS	Daily	--	--	1.97
13D10S	Bloody Dick Creek	45.1667	113.5000	29.1	1980	1992	7,550	NRCS	Daily	--	--	1.22
13D19S	Darkhorse Lake	45.1667	113.5833	49.4	1981	1992	8,700	NRCS	Daily	--	--	1.66
13D22S	Saddle Mountain	45.7000	113.9667	42.6	1980	1992	7,900	NRCS	Daily	--	--	1.50
13D26S	Calvert Creek	45.8833	113.3333	19.1	1980	1992	6,430	NRCS	Daily	--	--	1.05
13E23S	Lemhi Ridge	44.9833	113.4333	28.2	1980	1992	8,100	NRCS	Daily	--	--	1.38
14A11S	Grave Creek	48.9167	114.7667	49.9	1980	1992	4,300	NRCS	Daily	--	--	2.50
14A12S	Stahl Peak	48.9167	114.8667	64.6	1980	1992	6,030	NRCS	Daily	--	--	2.61
14A14S	Hand Creek	48.3000	114.8333	31.2	1980	1992	5,035	NRCS	Daily	--	--	1.74
14C12S	Twin Lakes	46.1500	114.5000	66.3	1980	1992	6,400	NRCS	Daily	--	--	2.23
14C13S	Twelvemile Creek	46.1500	114.4500	45.5	1981	1992	5,600	NRCS	Daily	--	--	1.77
14D02S	Nez Perce Camp	45.7333	114.4833	35.1	1981	1992	5,650	NRCS	Daily	--	--	1.49
15C10S	Hoodoo Basin	46.9833	115.0333	81.5	1981	1992	6,050	NRCS	Daily	--	--	2.91
240019	Absarokee	45.5500	109.3833	17.0	1972	1991	3,880	NWS	Hourly	0.80	1.12	1.88
240075	Alberton	47.0000	114.4833	20.0	1958	1974	3,070	NWS	Daily	--	--	1.13
240088	Albion 6 Ne	45.2500	104.2000	15.0	1948	1992	3,290	NWS	Daily	--	--	1.60
240100	Alder	45.3167	112.1167	15.0	1950	1979	5,120	NWS	Daily	--	--	1.00
240110	Alder 17 S	45.0667	112.0667	13.3	1957	1992	5,850	NWS	Daily	--	--	1.25
240115	Alder Ruby Dam	45.2500	112.1167	15.0	1981	1992	5,290	NWS	Daily	--	--	1.11

Table 1. Precipitation stations, Montana and northern Wyoming, and pertinent station information (Continued)

Station no.	Name	Latitude, in decimal degrees	Longitude, in decimal degrees	Mean annual precipitation, in inches	Period of station record used in analysis		Elevation, in feet above sea level	Agency	Type of gage	Mean storm depth, in inches, for indicated duration, in hours		
					Begin date	End date				2	6	24
240165	Alzada	45.0333	104.4000	15.0	1949	1991	3,440	NWS	Hourly	.73	.95	1.35
240199	Anaconda	46.1333	112.9500	13.0	1906	1992	5,280	NWS	Daily	--	--	1.15
240202	Anceney	45.6500	111.3667	15.0	1952	1972	4,760	NWS	Daily	--	--	1.28
240236	Apex 2 NW	45.4000	112.7167	11.0	1950	1977	5,400	NWS	Daily	--	--	1.02
240255	Argenta	45.2833	112.8667	16.0	1949	1958	6,000	NWS	Daily	--	--	1.11
240274	Armstead	44.9667	112.8667	15.0	1950	1963	5,500	NWS	Hourly	.47	.75	1.13
240330	Ashland Ranger Station	45.6000	106.2667	15.0	1940	1991	3,020	NWS	Hourly	.74	1.00	1.35
240364	Augusta	47.4833	112.3833	13.1	1901	1991	4,070	NWS	Hourly	.74	.97	1.60
240375	Austin 1 W	46.6500	112.2667	15.7	1950	1992	5,000	NWS	Daily	--	--	1.31
240392	Babb 6 NE	48.9333	113.3667	17.2	1914	1992	4,300	NWS	Daily	--	--	1.83
240412	Baker	46.3667	104.2667	14.6	1937	1992	2,930	NWS	Daily	--	--	1.57
240432	Ballantine	45.9500	108.1333	14.6	1919	1990	3,000	NWS	Daily	--	--	1.42
240466	Barber	46.3167	109.3667	12.4	1949	1991	3,730	NWS	Daily	--	--	1.41
240515	Basin	46.2667	112.2667	20.0	1950	1969	5,360	NWS	Daily	--	--	1.07
240554	Baylor	48.6667	106.4833	13.0	1940	1991	2,930	NWS	Hourly	.79	1.02	1.40
240617	Belfry 4 SSW	45.0833	109.0333	10.0	1952	1974	3,900	NWS	Daily	--	--	1.12
240622	Belgrade Ap	45.7833	111.1500	14.7	1941	1992	4,450	NWS	Hourly	.47	.70	1.11
240636	Belltower	45.6500	104.3833	13.8	1951	1992	3,300	NWS	Daily	--	--	1.56
240739	Biddle	45.1000	105.3333	12.6	1951	1992	3,330	NWS	Daily	--	--	1.55
240743	Biddle 8 SW	45.0500	105.4667	13.9	1963	1992	3,600	NWS	Daily	--	--	1.81
240755	Bigfork 13 S	47.8833	114.0333	22.4	1939	1992	3,010	NWS	Daily	--	--	1.72
240770	Big Sandy	48.1667	110.1167	13.9	1922	1992	2,700	NWS	Daily	--	--	1.72
240780	Big Timber	45.8333	109.9500	15.4	1910	1992	4,100	NWS	Daily	--	--	1.65
240802	Billings Water Plant	45.7667	108.4833	13.9	1902	1992	3,100	NWS	Daily	--	--	1.66
240807	Billings WSO AP	45.8000	108.5333	15.1	1933	1992	3,570	NWS	Hourly	.69	.92	1.46
240819	Birney	45.3167	106.5167	13.7	1955	1992	3,160	NWS	Daily	--	--	1.47
240877	Blackleaf	48.0167	112.4333	13.5	1950	1992	4,240	NWS	Daily	--	--	1.65
240923	Bloomfield	47.4167	104.9167	15.0	1969	1990	2,620	NWS	Daily	--	--	1.63
240926	Bloomfield 6 E	47.4167	104.8000	15.0	1949	1981	2,550	NWS	Hourly	.95	1.18	1.58
241008	Boulder St School	46.2333	112.1167	11.7	1940	1992	4,900	NWS	Hourly	.52	.67	.97

Table 1. Precipitation stations, Montana and northern Wyoming, and pertinent station information (Continued)

Station no.	Name	Latitude, in decimal degrees	Longi-tude, in decimal degrees	Mean annual precipita-tion, in inches	Period of station record used in analysis		Elevation, in feet above sea level	Agency	Type of gage	Mean storm depth, in inches, for indicated duration, in hours		
					Begin date	End date				2	6	24
241040	Boyes	45.2667	105.0167	15.0	1950	1971	3,330	NWS	Daily	--	--	1.58
241044	Bozeman Mon St Univ	45.6667	111.0500	19.2	1900	1992	4,860	NWS	Daily	--	--	1.37
241047	Bozeman 6 W Exp Farm	45.6667	111.1500	15.0	1967	1992	4,780	NWS	Hourly	.47	.66	1.26
241050	Bozeman 12 NE	45.8167	110.8833	35.2	1950	1992	5,950	NWS	Daily	--	--	2.03
241080	Brady Aznoe	47.9500	111.3333	15.0	1914	1992	3,330	NWS	Daily	--	--	1.40
241084	Brandenberg	45.8167	106.2167	14.5	1956	1992	2,770	NWS	Daily	--	--	1.46
241088	Bredette	48.5500	105.2667	12.2	1940	1992	2,690	NWS	Hourly	.84	1.04	1.47
241102	Bridger	45.3000	108.9167	13.7	1910	1992	3,680	NWS	Hourly	.45	.74	1.42
241127	Broadus	45.4333	105.4000	13.7	1940	1992	3,030	NWS	Hourly	.80	1.04	1.41
241149	Broadview	46.1000	108.8833	13.7	1952	1990	3,880	NWS	Daily	--	--	1.49
241169	Brockway 3 WSW	47.2833	105.8167	11.8	1960	1992	2,630	NWS	Daily	--	--	1.71
241202	Browning	48.5667	113.0167	15.6	1900	1991	4,360	NWS	Hourly	.61	1.02	1.80
241231	Brusett 3 W	47.4167	107.3333	13.3	1949	1992	3,270	NWS	Daily	--	--	1.58
241297	Busby	45.5333	106.9500	14.9	1914	1992	3,430	NWS	Daily	--	--	1.49
241309	Butte 8 S	45.9000	112.5500	15.0	1954	1991	5,700	NWS	Hourly	.52	.68	1.13
241313	Butte Schl Of Mines	46.0167	112.5500	15.0	1948	1959	5,770	NWS	Daily	--	--	1.05
241318	Butte FAA AP	45.9500	112.5000	12.1	1900	1992	5,540	NWS	Hourly	--	.73	1.16
241342	Bynum 4 SSE	47.9333	112.3000	15.0	1951	1979	4,020	NWS	Daily	--	--	1.48
241408	Cameron	45.2000	111.6833	16.0	1940	1991	5,500	NWS	Hourly	.49	.72	1.00
241418	Campbell Farm Camp 4	45.4167	107.9000	20.0	1940	1960	3,650	NWS	Daily	--	--	1.83
241450	Canyon Creek	46.8167	112.2500	15.0	1945	1977	4,310	NWS	Daily	--	--	1.11
241470	Canyon Ferry Dam	46.6500	111.7333	11.8	1957	1992	3,670	NWS	Daily	--	--	1.18
241500	Cardwell	45.8667	111.9500	10.0	1949	1990	4,280	NWS	Hourly	.52	.74	1.11
241518	Carlyle 12 NW	46.7667	104.2833	15.4	1962	1992	3,030	NWS	Daily	--	--	1.86
241525	Carter 14 W	47.7833	111.2167	15.0	1983	1992	3,450	NWS	Daily	--	--	1.61
241552	Cascade 5 S	47.2167	111.7167	15.9	1904	1992	3,390	NWS	Daily	--	--	1.75
241557	Cascade 20 SSE	47.0000	111.5833	14.9	1956	1992	4,600	NWS	Daily	--	--	1.45
241692	Chester	48.5167	110.9500	10.6	1943	1992	3,140	NWS	Daily	--	--	1.25
241722	Chinook	48.5833	109.2333	12.4	1948	1992	2,340	NWS	Daily	--	--	1.62
241737	Choteau Airport	47.8167	112.1667	10.6	1905	1992	3,950	NWS	Hourly	.65	.87	1.46

Table 1. Precipitation stations, Montana and northern Wyoming, and pertinent station information (Continued)

Station no.	Name	Latitude, in decimal degrees	Longitude, in decimal degrees	Mean annual precipitation, in inches	Period of station record used in analysis		Elevation, in feet above sea level	Agency	Type of gage	Mean storm depth, in inches, for indicated duration, in hours		
					Begin date	End date				2	6	24
241758	Circle	47.4333	105.5833	13.3	1964	1992	2,440	NWS	Daily	--	--	1.73
241765	Circle 7 N	47.5167	105.5667	13.0	1931	1963	2,430	NWS	Daily	--	--	1.58
241781	Clark Canyon Dam	45.0000	112.7833	15.0	1964	1991	5,580	NWS	Hourly	.47	.67	1.02
241824	Cleveland 5 ENE	48.3167	109.0667	15.9	1958	1989	3,330	NWS	Daily	--	--	2.10
241875	Cohagen	47.0500	106.6167	15.0	1940	1992	2,720	NWS	Hourly	.71	.99	1.40
241919	Columbia Falls 5 SW	48.3167	114.2000	20.0	1900	1948	3,080	NWS	Daily	--	--	1.44
241938	Columbus	45.6333	109.2333	14.7	1929	1992	3,590	NWS	Daily	--	--	1.73
241968	Conner	45.9333	114.1333	16.0	1956	1971	4,030	NWS	Daily	--	--	1.14
241974	Conrad Airport	48.1667	111.9667	11.9	1911	1992	3,540	NWS	Daily	--	--	1.54
241984	Content 1 SE	47.9833	107.5500	14.0	1940	1992	2,340	NWS	Hourly	.83	1.05	1.53
241995	Cooke City 2 W	45.0167	109.9667	25.6	1968	1992	7,460	NWS	Hourly	.43	.66	1.20
242054	Corwin Springs 1 NNW	45.1333	110.8167	16.0	1952	1971	5,130	NWS	Hourly	.44	.63	.98
242104	Creston	48.1833	114.1333	20.0	1949	1992	2,940	NWS	Daily	--	--	1.45
242112	Crow Agency	45.6000	107.4500	15.9	1900	1989	3,030	NWS	Daily	--	--	1.66
242122	Culbertson	48.1500	104.5000	13.9	1901	1992	1,920	NWS	Daily	--	--	1.72
242158	Custer	46.1333	107.5333	15.0	1940	1975	2,740	NWS	Hourly	.63	.88	1.38
242173	Cut Bank FAA AP	48.6000	112.3667	11.8	1909	1992	3,840	NWS	Hourly	.51	.84	1.45
242221	Darby	46.0167	114.1667	15.8	1926	1992	3,880	NWS	Hourly	.42	.64	1.12
242266	Decker 4 NNE	45.0500	106.8000	12.7	1950	1992	3,500	NWS	Daily	--	--	1.58
242272	Deep Creek Pass 2	46.3667	111.1333	25.0	1978	1992	5,440	NWS	Daily	--	--	1.49
242273	Deer Lodge	46.3833	112.7333	15.0	1913	1958	4,530	NWS	Daily	--	--	1.12
242275	Deer Lodge 3 W	46.4000	112.8000	10.7	1959	1992	4,850	NWS	Daily	--	--	1.01
242301	Del Bonita	49.0000	112.7833	14.6	1951	1992	4,340	NWS	Daily	--	--	1.80
242317	Delphia	46.4833	108.4000	15.0	1945	1982	3,060	NWS	Hourly	.58	.80	1.28
242347	Denton 1 NNE	47.3333	109.9500	15.1	1922	1992	3,620	NWS	Daily	--	--	1.59
242404	Dillon Airport	45.2500	112.5500	10.2	1940	1991	5,220	NWS	Hourly	.44	.65	1.03
242409	Dillon W M C E	45.2000	112.6333	11.6	1900	1992	5,230	NWS	Daily	--	--	1.24
242414	Dillon 9 SSE	45.0833	112.6000	15.0	1950	1991	5,500	NWS	Hourly	.45	.68	1.13
242421	Divide 2 NW	45.7667	112.7833	12.6	1949	1992	5,410	NWS	Hourly	.50	.69	1.10
242438	Dodson	48.4000	108.2500	10.8	1951	1992	2,280	NWS	Daily	--	--	1.52

Table 1. Precipitation stations, Montana and northern Wyoming, and pertinent station information (Continued)

Station no.	Name	Latitude, in decimal degrees	Longitude, in decimal degrees	Mean annual precipitation, in inches	Period of station record used in analysis		Elevation, in feet above sea level	Agency	Type of gage	Mean storm depth, in inches, for indicated duration, in hours		
					Begin date	End date				2	6	24
242441	Dodson 11 N	48.5500	108.2000	15.0	1953	1991	2,710	NWS	Hourly	.69	.93	1.39
242477	Dovetail	47.3500	108.2500	15.0	1940	1971	2,740	NWS	Hourly	.68	.94	1.46
242500	Drummond Aviation	46.6667	113.1500	15.0	1929	1992	3,940	NWS	Hourly	.49	.68	1.02
242550	Dunkirk 15 NNE	48.7000	111.6000	15.0	1912	1977	3,380	NWS	Daily	--	--	1.32
242571	Dupuyer	48.2000	112.5000	15.0	1950	1975	4,130	NWS	Hourly	.63	.95	1.75
242576	Dupuyer 7 WNW	48.2500	112.6333	16.0	1962	1978	4,100	NWS	Daily	--	--	1.53
242584	Dutton 6 E	47.8500	111.5833	15.0	1940	1991	3,590	NWS	Hourly	.67	.95	1.53
242629	East Glacier	48.4500	113.2167	28.5	1953	1992	4,810	NWS	Daily	--	--	1.93
242661	Edgar 9 SE	45.3833	108.7167	19.0	1951	1973	4,000	NWS	Daily	--	--	2.30
242689	Ekalaka	45.8833	104.5333	16.7	1900	1992	3,430	NWS	Hourly	.84	1.11	1.64
242719	Elkhorn Hot Spgs	45.4667	113.1167	25.0	1950	1991	7,390	NWS	Hourly	.42	.64	1.06
242738	Elliston	46.5667	112.4333	20.0	1951	1976	5,080	NWS	Daily	--	--	1.23
242778	Emigrant	45.3667	110.7167	20.0	1950	1967	5,000	NWS	Daily	--	--	.99
242793	Ennis	45.3500	111.7167	13.3	1918	1992	4,950	NWS	Daily	--	--	1.09
242812	Essex	48.2833	113.6167	49.0	1952	1991	3,870	NWS	Hourly	.46	.82	1.80
242820	Ethridge	48.5667	112.1333	10.9	1949	1992	3,540	NWS	Daily	--	--	1.42
242827	Eureka R S	48.9000	115.0667	14.5	1960	1992	2,530	NWS	Hourly	.49	.64	.95
242857	Fairfield	47.6167	111.9833	12.4	1927	1992	3,980	NWS	Daily	--	--	1.48
242867	Fairview	47.8500	104.0500	15.0	1933	1955	1,930	NWS	Daily	--	--	1.73
242996	Fishtail	45.4500	109.5167	18.5	1952	1992	4,500	NWS	Daily	--	--	1.93
243013	Flatwillow 4 ENE	46.8500	108.3167	13.6	1913	1992	3,140	NWS	Daily	--	--	1.47
243089	Forks 4 NNE	48.7833	107.4667	12.6	1915	1992	2,600	NWS	Daily	--	--	1.66
243098	Forsyth	46.2667	106.6667	15.0	1976	1992	2,520	NWS	Daily	--	--	1.47
243099	Forsyth 2 E	46.2667	106.6167	15.0	1948	1975	2,720	NWS	Daily	--	--	1.55
243110	Fort Assinniboine	48.5000	109.8000	12.0	1917	1992	2,610	NWS	Daily	--	--	1.49
243113	Fort Benton	47.8167	110.6667	14.4	1938	1992	2,640	NWS	Daily	--	--	1.60
243119	Fort Benton 20 NW	48.0333	110.9833	15.0	1961	1981	3,400	NWS	Hourly	.65	.94	1.50
243139	Fortine 1 N	48.7833	114.9000	16.5	1906	1992	3,000	NWS	Daily	--	--	1.26
243157	Fort Logan 3 ESE	46.6667	111.1167	10.9	1951	1992	4,700	NWS	Daily	--	--	1.11
243176	Fort Peck Pwr Pl	48.0167	106.4000	11.7	1940	1992	2,070	NWS	Hourly	.94	1.20	1.69

Table 1. Precipitation stations, Montana and northern Wyoming, and pertinent station information (Continued)

Station no.	Name	Latitude, in decimal degrees	Longitude, in decimal degrees	Mean annual precipitation, in inches	Period of station record used in analysis		Elevation, in feet above sea level	Agency	Type of gage	Mean storm depth, in inches, for indicated duration, in hours		
					Begin date	End date				2	6	24
243238	Four Buttes	48.8000	105.6000	14.0	1951	1974	2,480	NWS	Hourly	.71	1.20	1.65
243280	Frazer	48.0667	106.0500	10.0	1924	1966	2,070	NWS	Daily	--	--	1.58
243309	Froid	48.3333	104.5000	15.0	1940	1991	2,030	NWS	Hourly	.79	1.03	1.36
243346	Galata 16 SSW	48.2500	111.4167	12.5	1950	1992	3,100	NWS	Daily	--	--	1.53
243366	Gallatin Gateway 10 SSW	45.4500	111.2333	22.8	1950	1992	5,480	NWS	Daily	--	--	1.75
243372	Gallatin Gateway 26 SSW	45.2167	111.2833	27.0	1967	1983	6,600	NWS	Daily	--	--	1.33
243378	Gardiner	45.0333	110.6833	10.7	1956	1992	5,280	NWS	Daily	--	--	1.00
243445	Geraldine	47.6000	110.2667	14.5	1951	1992	3,130	NWS	Daily	--	--	1.78
243479	Gibbons Pass	45.7000	113.9500	38.0	1940	1991	7,000	NWS	Hourly	.55	.85	1.52
243486	Gibson 2 NE	46.0333	109.5000	14.8	1952	1992	4,350	NWS	Daily	--	--	1.56
243489	Gibson Dam	47.6000	112.7667	17.8	1914	1992	4,590	NWS	Hourly	.64	1.12	1.88
243530	Gilford	48.5833	110.3000	18.0	1959	1992	2,820	NWS	Daily	--	--	1.56
243554	Glasgow 15 NW	48.3833	106.8333	10.9	1951	1992	2,240	NWS	Daily	--	--	1.70
243557	Glasgow	48.1833	106.6333	11.0	1902	1955	2,090	NWS	Daily	--	--	1.77
243558	Glasgow WSO AP	48.2167	106.6167	10.9	1956	1992	2,280	NWS	Hourly	.91	1.16	1.60
243570	Glen 4 N	45.5167	112.6833	9.1	1958	1992	5,050	NWS	Daily	--	--	1.01
243581	Glendive	47.1000	104.7167	13.6	1900	1992	2,080	NWS	Hourly	.98	1.28	1.82
243617	Goldbutte 7 N	48.9833	111.4000	13.0	1914	1992	3,500	NWS	Daily	--	--	1.52
243707	Grant 4 NE	45.0500	113.1167	9.6	1950	1992	5,840	NWS	Daily	--	--	1.03
243727	Grass Range	47.0333	108.8000	16.8	1935	1992	3,480	NWS	Daily	--	--	1.69
243749	N Great Falls	47.5167	111.3000	15.2	1900	1948	3,350	NWS	Daily	--	--	1.49
243751	Great Falls WSCMO AP	47.4833	111.3667	15.2	1900	1992	3,660	NWS	Hourly	.72	.96	1.64
243885	Hamilton	46.2500	114.1500	13.3	1900	1992	3,530	NWS	Daily	--	--	1.12
243910	Harb	48.1833	107.4833	15.0	1951	1984	2,420	NWS	Daily	--	--	1.61
243915	Hardin	45.7167	107.6000	12.7	1941	1991	2,910	NWS	Daily	--	--	1.46
243929	Harlem 4 W	48.5500	108.8500	11.7	1930	1992	2,360	NWS	Daily	--	--	1.57
243939	Harlowton	46.4333	109.8333	13.8	1914	1992	4,140	NWS	Daily	--	--	1.46
243984	Haugan 3 E (Deborgia)	47.3833	115.3500	27.6	1912	1990	3,120	NWS	Hourly	.47	.85	1.59
243996	Havre WSO AP	48.5500	109.7667	11.1	1900	1992	2,580	NWS	Hourly	.68	.92	1.43
244007	Haxby 18 SW	47.5667	106.7000	13.7	1951	1991	2,650	NWS	Daily	--	--	1.64

Table 1. Precipitation stations, Montana and northern Wyoming, and pertinent station information (Continued)

Station no.	Name	Latitude, in decimal degrees	Longitude, in decimal degrees	Mean annual precipitation, in inches	Period of station record used in analysis		Elevation, in feet above sea level	Agency	Type of gage	Mean storm depth, in inches, for indicated duration, in hours		
					Begin date	End date				2	6	24
244020	Hays	48.0000	108.7000	18.0	1941	1964	3,530	NWS	Hourly	.55	.87	1.44
244038	Hebgen Dam	44.8667	111.3333	30.1	1914	1992	6,490	NWS	Hourly	.54	.77	1.22
244050	Helena 6 N	46.6667	112.0500	15.0	1948	1979	3,800	NWS	Daily	--	--	1.12
244055	Helena WSO AP	46.6000	112.0000	11.6	1900	1992	3,890	NWS	Hourly	.60	.76	1.19
244084	Heron 2 NW	48.0833	116.0000	33.9	1912	1992	2,240	NWS	Daily	--	--	1.74
244120	Highwood	47.5500	110.7833	15.0	1951	1992	3,400	NWS	Hourly	.62	.95	1.82
244133	Highwood 7 NE	47.6500	110.6667	18.0	1949	1983	3,600	NWS	Daily	--	--	2.20
244143	Hilger	47.2500	109.3500	20.0	1940	1991	4,080	NWS	Hourly	.72	1.03	1.71
244172	Hingham	48.5500	110.4333	12.0	1951	1983	3,030	NWS	Daily	--	--	1.48
244177	Hinsdale 1 E	48.4000	107.0500	12.0	1948	1970	2,150	NWS	Daily	--	--	1.61
244180	Hinsdale 4 SW	48.3500	107.1500	13.0	1971	1992	2,680	NWS	Daily	--	--	1.92
244182	Hinsdale 23 N	48.7500	107.0833	14.0	1952	1972	2,430	NWS	Daily	--	--	1.72
244193	Hobson	47.0000	109.8667	15.0	1924	1983	4,080	NWS	Daily	--	--	1.41
244217	Hogeland 7 WSW	48.8167	108.8000	15.0	1951	1980	3,350	NWS	Daily	--	--	1.60
244241	Holter Dam	47.0000	112.0167	11.8	1920	1992	3,490	NWS	Hourly	.56	.79	1.32
244297	Hot Springs	47.6167	114.6500	15.0	1970	1990	2,780	NWS	Daily	--	--	1.15
244328	Hungry Horse Dam	48.3500	114.0000	34.5	1948	1992	3,160	NWS	Daily	--	--	1.81
244345	Huntley Exp Stn	45.9167	108.2500	14.2	1911	1992	2,990	NWS	Daily	--	--	1.45
244358	Hysham	46.3000	107.2333	13.3	1948	1992	2,660	NWS	Daily	--	--	1.56
244364	Hysham 25 SSE	45.9000	107.1333	14.3	1960	1992	3,100	NWS	Daily	--	--	1.42
244368	Iliad	47.8000	109.7833	12.9	1940	1992	2,950	NWS	Hourly	.61	.86	1.29
244386	Ingomar 11 NE	46.7000	107.2167	11.1	1954	1992	2,780	NWS	Daily	--	--	1.44
244442	Ismay	46.5000	104.8000	15.0	1940	1991	2,500	NWS	Hourly	.88	1.09	1.49
244447	Jackson 1 SE	45.3667	113.4000	11.7	1950	1992	6,570	NWS	Daily	--	--	1.03
244462	Jardine	45.0667	110.6333	18.0	1951	1976	6,450	NWS	Daily	--	--	1.36
244506	Joliet	45.4833	108.9667	16.3	1952	1992	3,700	NWS	Daily	--	--	1.78
244512	Joplin	48.5667	110.7667	10.2	1933	1992	3,300	NWS	Hourly	.62	.89	1.41
244522	Jordan	47.3167	106.9000	13.0	1905	1992	2,590	NWS	Daily	--	--	1.61
244527	Jordan 22 E (Van Norman)	47.3500	106.4333	14.0	1966	1985	2,380	NWS	Daily	--	--	1.60
244538	Judith Gap	46.6833	109.7500	15.9	1950	1992	4,690	NWS	Daily	--	--	1.63

Table 1. Precipitation stations, Montana and northern Wyoming, and pertinent station information (Continued)

Station no.	Name	Latitude, in decimal degrees	Longi-tude, in decimal degrees	Mean annual precipita-tion, in inches	Period of station record used in analysis		Elevation, in feet above sea level	Agency	Type of gage	Mean storm depth, in inches, for indicated duration, in hours		
					Begin date	End date				2	6	24
244545	Judith Gap 13 E	46.6833	109.4833	19.0	1965	1992	5,100	NWS	Daily	--	--	1.60
244558	Kalispell WSO AP	48.3000	114.2667	16.5	1900	1992	2,970	NWS	Hourly	.55	.79	1.16
244563	Kalispell	48.2000	114.3000	20.0	1941	1980	2,970	NWS	Hourly	--	.70	1.21
244645	Kila	48.1333	114.4667	20.0	1964	1990	3,190	NWS	Daily	--	--	1.18
244663	Kings Hill Showdown	46.8333	110.7000	35.0	1938	1965	7,200	NWS	Hourly	.57	.88	1.43
244701	Kirby 1 S	45.3167	106.9833	19.0	1960	1975	3,950	NWS	Daily	--	--	1.86
244715	Knobs	45.9167	104.0833	13.7	1952	1992	3,000	NWS	Daily	--	--	1.55
244766	Kremlin	48.5333	110.1000	11.3	1951	1992	2,860	NWS	Daily	--	--	1.62
244820	Lakeview	44.6000	111.8000	20.4	1940	1992	6,710	NWS	Hourly	.59	.87	1.42
244830	Lambert	47.6833	104.6167	15.0	1956	1973	2,340	NWS	Daily	--	--	1.95
244839	Lame Deer	45.6167	106.6500	15.4	1938	1992	3,350	NWS	Daily	--	--	1.65
244894	Laurel	45.6667	108.7833	15.2	1952	1992	3,310	NWS	Daily	--	--	1.67
244904	Lavina	46.3000	108.9333	15.0	1940	1991	3,430	NWS	Hourly	.64	.93	1.36
244954	Lennep 6 WSW	46.4000	110.6833	16.3	1960	1992	5,880	NWS	Daily	--	--	1.27
244978	Lewistown 10 S	46.9167	109.4167	24.2	1949	1992	4,900	NWS	Daily	--	--	2.07
244983	Lewistown 2 SW	47.0500	109.4500	20.0	1900	1992	4,100	NWS	Hourly	.72	.98	1.68
245009	Libby Dam	48.4000	115.3000	26.0	1970	1986	2,200	NWS	Daily	--	--	1.04
245015	Libby 1 NE R S	48.4000	115.5333	18.5	1912	1992	2,140	NWS	Hourly	.48	.73	1.14
245020	Libby 32 SSE	47.9667	115.2167	17.0	1949	1992	3,600	NWS	Daily	--	--	1.35
245030	Lima	44.6500	112.5833	25.0	1900	1992	6,270	NWS	Hourly	.48	.63	.96
245032	Lima Dam	44.6667	112.3667	21.0	1949	1958	6,700	NWS	Daily	--	--	.97
245040	Lincoln R S	46.9500	112.6500	10.0	1948	1992	4,580	NWS	Hourly	.55	.75	1.37
245043	Lindbergh Lake	47.4000	113.7167	27.6	1959	1992	4,500	NWS	Daily	--	--	1.54
245045	Lindsay	47.2333	105.1500	13.7	1950	1992	2,690	NWS	Daily	--	--	1.84
245076	Livingston	45.6667	110.5667	15.0	1900	1981	4,490	NWS	Daily	--	--	1.32
245080	Livingston 12 S	45.4833	110.5667	20.0	1952	1992	4,870	NWS	Daily	--	--	1.48
245086	Livingston FAA AP	45.7000	110.4500	15.7	1940	1992	4,650	NWS	Hourly	.57	.77	1.21
245106	Lodge Grass	45.3000	107.3667	15.0	1940	1991	3,380	NWS	Hourly	.70	.97	1.61
245122	Logan	45.8833	111.4333	13.0	1972	1991	4,090	NWS	Hourly	.54	.72	1.21
245146	Lolo Hot Springs 2 NE	46.7500	114.5167	37.0	1960	1991	4,060	NWS	Hourly	.47	.72	1.27

Table 1. Precipitation stations, Montana and northern Wyoming, and pertinent station information (Continued)

Station no.	Name	Latitude, in decimal degrees	Longi-tude, in decimal degrees	Mean annual precipita-tion, in inches	Period of station record used in analysis: Begin date	End date	Elevation, in feet above sea level	Agency	Type of gage	Mean storm depth, in inches, for indicated duration, in hours: 2	6	24
245153	Loma 1 WNW	47.9333	110.5167	13.4	1950	1992	2,580	NWS	Daily	--	--	1.58
245164	Lonepine 1 WNW	47.7167	114.6500	15.0	1919	1969	2,880	NWS	Hourly	.37	.64	.90
245177	Lonesome Lake	48.2500	110.2000	14.0	1948	1980	2,760	NWS	Daily	--	--	1.52
245191	Loring 10 N	48.9500	107.8167	15.0	1951	1974	2,660	NWS	Daily	--	--	1.71
245195	Lost Lake	48.6500	108.3000	15.0	1940	1952	3,100	NWS	Hourly	--	.85	1.20
245235	Loweth	46.3667	110.7000	20.0	1948	1959	5,800	NWS	Daily	--	--	.90
245285	Lustre 4 NNW	48.4500	105.9333	12.0	1931	1992	2,920	NWS	Daily	--	--	1.47
245303	Mac Kenzie	46.1500	104.7333	15.0	1950	1992	2,810	NWS	Daily	--	--	1.66
245337	Malta	48.3500	107.8667	14.0	1906	1992	2,260	NWS	Daily	--	--	1.66
245340	Malta 35 S	47.8333	107.9667	12.8	1959	1992	2,620	NWS	Daily	--	--	1.82
245351	Manhattan	45.8667	111.3333	13.4	1952	1982	4,230	NWS	Daily	--	--	1.19
245387	Martinsdale 3 NNW	46.5000	110.3333	13.3	1941	1992	4,800	NWS	Hourly	.59	.82	1.28
245405	Marysville 3	46.7500	112.3000	23.0	1959	1971	5,380	NWS	Daily	--	--	1.46
245572	Medicine Lake 3 SE	48.4833	104.4500	13.3	1911	1992	1,950	NWS	Daily	--	--	1.62
245596	Melstone	46.6000	107.8667	15.0	1914	1992	2,920	NWS	Daily	--	--	1.57
245603	Melville 4 W	46.1000	110.0500	16.7	1960	1992	5,370	NWS	Daily	--	--	1.69
245608	Menard 3 NE	46.0167	111.1333	15.4	1952	1992	5,050	NWS	Daily	--	--	1.34
245666	Mildred	46.6833	104.9500	15.0	1909	1977	2,410	NWS	Daily	--	--	1.75
245668	Mildred 5 N	46.7667	104.9667	15.0	1979	1992	2,510	NWS	Daily	--	--	1.68
245685	Miles City	46.4000	105.8167	15.0	1900	1985	2,360	NWS	Hourly	.78	1.01	1.45
245690	Miles City FAA AP	46.4333	105.8667	14.1	1937	1992	2,630	NWS	Daily	--	--	1.57
245706	Millegan	47.0333	111.3667	17.0	1940	1991	4,500	NWS	Hourly	.64	.96	1.64
245735	Missoula 2 NE	46.9000	113.9667	20.0	1900	1992	3,420	NWS	Daily	--	--	1.21
245745	Missoula WSO AP	46.9167	114.0833	13.5	1941	1992	3,190	NWS	Hourly	.49	.74	1.11
245761	Moccasin Exp Stn	47.0500	109.9500	16.5	1909	1992	4,300	NWS	Daily	--	--	1.43
245791	Molt 6 SW	45.7667	108.9667	15.0	1940	1991	4,000	NWS	Hourly	.62	.89	1.28
245811	Monida	44.5667	112.3167	13.9	1949	1991	6,790	NWS	Daily	--	--	1.16
245870	Moorhead 9 NE	45.1833	105.7500	13.0	1958	1992	3,220	NWS	Daily	--	--	1.52
245872	Mosby 2 ENE	47.0000	107.8500	13.3	1959	1992	2,750	NWS	Daily	--	--	1.68
245873	Mosby 18 N	47.2500	107.9500	15.0	1955	1983	2,320	NWS	Daily	--	--	1.61

Table 1. Precipitation stations, Montana and northern Wyoming, and pertinent station information (Continued)

Station no.	Name	Latitude, in decimal degrees	Longi-tude, in decimal degrees	Mean annual precipita-tion, in inches	Period of station record used in analysis		Elevation, in feet above sea level	Agency	Type of gage	Mean storm depth, in inches, for indicated duration, in hours		
					Begin date	End date				2	6	24
245961	Mystic Lake	45.2333	109.7500	25.2	1928	1992	6,560	NWS	Daily	--	--	1.84
246008	Neihart 8 NNW	47.0500	110.7833	20.8	1967	1992	5,230	NWS	Hourly	.66	.99	1.89
246138	Nohly 4 NW	48.0333	104.1333	15.0	1951	1981	1,900	NWS	Daily	--	--	1.78
246153	Norris 3 ENE	45.5833	111.6500	15.0	1957	1981	4,800	NWS	Daily	--	--	1.56
246157	Norris Madison P H	45.4833	111.6333	17.7	1907	1992	4,750	NWS	Daily	--	--	1.67
246190	Nye 2	45.4333	109.8000	22.0	1951	1992	4,810	NWS	Daily	--	--	1.89
246236	Opheim 10 N	49.0000	106.3833	11.7	1957	1992	2,980	NWS	Daily	--	--	1.55
246238	Opheim 12 SSE	48.7000	106.3167	11.7	1948	1992	2,950	NWS	Daily	--	--	1.64
246287	Otter 9 SSW	45.1000	106.2500	18.5	1962	1989	4,060	NWS	Daily	--	--	1.93
246302	Ovando	47.0167	113.1333	20.0	1900	1992	4,110	NWS	Hourly	.53	.70	1.23
246307	Ovando 7 WNW	47.0500	113.2833	20.0	1950	1969	4,000	NWS	Daily	--	--	1.12
246364	Paradise	47.3833	114.8000	24.0	1962	1973	2,890	NWS	Daily	--	--	1.47
246426	Pendroy 2 NNW	48.1167	112.3333	15.2	1941	1989	4,370	NWS	Daily	--	--	1.67
246472	Philipsburg R S	46.3167	113.3000	14.6	1904	1992	5,270	NWS	Hourly	.52	.75	1.34
246475	Phillips 1 S	48.0667	108.1667	15.0	1951	1972	2,650	NWS	Daily	--	--	1.49
246562	Plains R S	47.4667	114.8833	20.0	1941	1991	2,490	NWS	Hourly	.47	.67	1.04
246576	Pleasant Valley	48.1333	114.9167	25.0	1923	1972	3,600	NWS	Daily	--	--	1.27
246580	Pleasant Valley 4 SE	48.1000	114.8667	25.0	1942	1990	3,670	NWS	Hourly	.47	.75	1.27
246586	Plentywood	48.7833	104.5500	12.8	1948	1992	2,040	NWS	Daily	--	--	1.56
246601	Plevna	46.4167	104.5000	14.4	1912	1992	2,770	NWS	Daily	--	--	1.66
246608	Polaris	45.3667	113.1167	16.0	1949	1958	6,700	NWS	Daily	--	--	1.46
246615	Polebridge	48.7667	114.2667	21.9	1942	1992	3,520	NWS	Hourly	.46	.74	1.31
246635	Polson	47.6833	114.1667	16.7	1907	1992	2,990	NWS	Daily	--	--	1.29
246640	Polson Kerr Dam	47.6833	114.2333	14.8	1951	1992	2,730	NWS	Daily	--	--	1.32
246655	Pony	45.6667	111.9000	17.4	1959	1992	5,580	NWS	Daily	--	--	1.56
246660	Poplar 2 E	48.1333	105.1500	26.0	1900	1990	2,000	NWS	Daily	--	--	1.78
246672	Port of Morgan	49.0000	107.8333	15.0	1976	1992	2,830	NWS	Daily	--	--	1.56
246685	Potomac	46.8833	113.5833	15.0	1965	1992	3,620	NWS	Daily	--	--	1.09
246691	Powderville 8 NNE	45.8500	105.0167	15.0	1949	1992	2,800	NWS	Daily	--	--	1.64
246700	Power 6 SE	47.6500	111.6000	26.0	1953	1992	3,750	NWS	Daily	--	--	1.47

Table 1. Precipitation stations, Montana and northern Wyoming, and pertinent station information (Continued)

Station no.	Name	Latitude, in decimal degrees	Longi-tude, in decimal degrees	Mean annual precipita-tion, in inches	Period of station record used in analysis: Begin date	End date	Elevation, in feet above sea level	Agency	Type of gage	Mean storm depth, in inches, for indicated duration, in hours: 2	6	24
246747	Pryor	45.4333	108.5333	17.2	1950	1992	4,000	NWS	Daily	--	--	1.87
246862	Rapelje 4 S	45.9167	109.2500	15.5	1908	1992	4,130	NWS	Daily	--	--	1.51
246893	Raymond Border Stn	49.0000	104.5833	13.0	1951	1992	2,350	NWS	Daily	--	--	1.71
246900	Raynesford	47.2833	110.7333	27.9	1954	1969	4,220	NWS	Daily	--	--	1.94
246902	Raynesford 2 NNW	47.3000	110.7500	20.0	1970	1992	4,220	NWS	Daily	--	--	1.63
246918	Red Lodge	45.1833	109.2500	25.8	1900	1992	5,580	NWS	Daily	--	--	2.06
246927	Redstone	48.8333	104.9500	12.3	1952	1992	2,110	NWS	Daily	--	--	1.58
246946	Reedpoint	45.7167	109.5500	15.0	1940	1991	3,740	NWS	Hourly	.61	.91	1.51
246976	Reserve 14 W	48.6167	104.7833	15.0	1947	1981	2,260	NWS	Hourly	.82	1.08	1.49
246986	Rexford R S	48.8833	115.2000	15.0	1944	1960	2,350	NWS	Hourly	.45	.68	1.09
247020	Richey	47.6333	105.0667	15.0	1948	1978	2,500	NWS	Daily	--	--	1.66
247028	Ridge 2 WSW	45.0333	105.0333	15.0	1952	1972	4,120	NWS	Hourly	.92	1.18	1.81
247034	Ridgeway 1 S	45.5000	104.4333	13.6	1952	1992	3,320	NWS	Daily	--	--	1.56
247128	Roberts 1 N	45.3667	109.1833	15.4	1952	1992	4,670	NWS	Daily	--	--	1.85
247136	Rock Springs	46.8167	106.2333	11.2	1931	1992	3,020	NWS	Daily	--	--	1.38
247148	Rocky Boy	48.2500	109.7833	16.4	1951	1986	3,690	NWS	Daily	--	--	2.20
247159	Rogers Pass 6 NNE	47.1667	112.3167	20.0	1953	1992	4,440	NWS	Daily	--	--	2.09
247204	Round Butte 1 NNE	47.5333	114.2833	15.0	1942	1991	3,100	NWS	Hourly	.51	.80	1.22
247214	Roundup	46.4500	108.5333	12.6	1914	1992	3,230	NWS	Daily	--	--	1.45
247228	Roy 8 NE	47.4333	108.8333	14.5	1939	1992	3,450	NWS	Daily	--	--	1.60
247234	Roy 24 NE (Mobridge)	47.6167	108.7000	13.8	1962	1992	2,310	NWS	Daily	--	--	1.70
247250	Rudyard 30 N	48.9833	110.5833	39.1	1961	1992	2,980	NWS	Daily	--	--	1.41
247258	Russell	48.0667	111.0667	15.0	1940	1991	3,200	NWS	Hourly	.63	.84	1.38
247263	Ryegate 18 NNW	46.5333	109.3833	12.8	1963	1992	4,480	NWS	Daily	--	--	1.56
247267	Saco Nelson Reservoir	48.5000	107.5167	13.0	1953	1992	2,230	NWS	Daily	--	--	1.55
247286	Saint Ignatius	47.3167	114.1000	16.7	1909	1992	2,900	NWS	Daily	--	--	1.35
247292	Saint Mary	48.7500	113.4333	30.0	1981	1992	4,560	NWS	Hourly	.64	1.05	1.99
247316	St Regis Clark Fork	47.3000	115.0833	20.0	1972	1991	2,600	NWS	Hourly	.57	.79	1.21
247318	Saint Regis R S	47.3000	115.1000	20.6	1961	1992	2,680	NWS	Daily	--	--	1.18
247362	Santa Rita 20 N	48.9833	112.3167	15.0	1950	1989	4,090	NWS	Daily	--	--	1.63

Table 1. Precipitation stations, Montana and northern Wyoming, and pertinent station information (Continued)

Station no.	Name	Latitude, in decimal degrees	Longi-tude, in decimal degrees	Mean annual precipita-tion, in inches	Period of station record used in analysis		Elevation, in feet above sea level	Agency	Type of gage	Mean storm depth, in inches, for indicated duration, in hours		
					Begin date	End date				2	6	24
247367	Sappington	45.8000	111.7667	10.0	1951	1963	4,200	NWS	Hourly	.38	.62	.91
247382	Savage	47.4500	104.3500	13.6	1906	1992	1,990	NWS	Daily	--	--	1.79
247424	Scobey	48.7833	105.4167	15.0	1924	1992	2,460	NWS	Daily	--	--	1.71
247425	Scobey 3 N	48.8333	105.4333	15.0	1980	1991	2,480	NWS	Hourly	.85	1.07	1.33
247448	Seeley Lake R S	47.2167	113.5167	21.5	1937	1992	4,100	NWS	Hourly	.54	.81	1.26
247501	Shelby AP	48.5500	111.8667	15.0	1940	1991	3,430	NWS	Hourly	.67	.89	1.39
247540	Shonkin 7 S	47.5333	110.5833	28.7	1953	1992	4,300	NWS	Daily	--	--	3.14
247560	Sidney	47.7333	104.1500	13.7	1911	1992	1,920	NWS	Daily	--	--	1.73
247605	Silver Lake	46.1667	113.2167	25.0	1950	1983	6,480	NWS	Daily	--	--	1.26
247610	Silver Star	45.6833	112.2833	10.0	1949	1991	4,530	NWS	Hourly	.44	.63	.98
247618	Simms	47.5000	111.9167	15.0	1972	1984	3,590	NWS	Hourly	.65	.88	1.48
247620	Simpson 6 NW	48.9833	110.3167	9.9	1938	1992	2,740	NWS	Daily	--	--	1.39
247740	Sonnette 2 WNW	45.4167	105.8500	18.0	1966	1992	3,900	NWS	Daily	--	--	1.73
247800	Springdale	45.7333	110.2333	44.5	1952	1992	4,220	NWS	Daily	--	--	1.41
247858	Stanford	47.1500	110.2167	19.0	1927	1992	4,280	NWS	Daily	--	--	1.48
247864	Stanford 1 WNW	47.1500	110.2500	19.0	1965	1992	4,310	NWS	Daily	--	--	1.76
247894	Stevensville	46.5167	114.1000	12.3	1912	1992	3,380	NWS	Hourly	.50	.67	1.04
247964	Sula 3 ENE	45.8500	113.9500	16.3	1956	1992	4,480	NWS	Daily	--	--	1.09
247978	Summit	48.3167	113.3500	42.0	1936	1991	5,230	NWS	Hourly	.54	.97	1.88
247996	Sunburst 8 E	48.9000	111.7333	12.1	1951	1992	3,610	NWS	Daily	--	--	1.49
248021	Sun River 4 S	47.4833	111.7333	12.5	1942	1992	3,600	NWS	Daily	--	--	1.43
248043	Superior	47.2000	114.8833	16.6	1915	1992	2,710	NWS	Daily	--	--	1.22
248087	Swan Lake	47.9167	113.8333	28.4	1941	1992	3,190	NWS	Hourly	.53	.88	1.57
248093	Sweetgrass	49.0000	111.9500	13.5	1951	1992	3,470	NWS	Daily	--	--	1.89
248101	Swift Dam	48.1667	112.8500	26.0	1966	1991	4,780	NWS	Hourly	.58	1.06	2.04
248161	Telegraph Creek	47.8000	107.6000	14.0	1932	1974	2,540	NWS	Daily	--	--	1.68
248165	Terry	46.8000	105.3000	11.5	1949	1992	2,250	NWS	Daily	--	--	1.52
248169	Terry 21 NNW	47.0667	105.5000	13.7	1940	1992	3,260	NWS	Hourly	.90	1.14	1.69
248202	Thoeny 1 E	48.8833	106.8833	15.0	1951	1965	2,460	NWS	Daily	--	--	1.48
248211	Thompson Falls P H	47.6000	115.3667	23.0	1912	1992	2,380	NWS	Daily	--	--	1.31

Table 1. Precipitation stations, Montana and northern Wyoming, and pertinent station information (Continued)

Station no.	Name	Latitude, in decimal degrees	Longitude, in decimal degrees	Mean annual precipitation, in inches	Period of station record used in analysis: Begin date	End date	Elevation, in feet above sea level	Agency	Type of gage	Mean storm depth, in inches, for indicated duration, in hours: 2	6	24
248233	Tiber Dam	48.3167	111.0833	10.7	1949	1992	2,850	NWS	Daily	--	--	1.33
248313	Toston 2 SW	46.1500	111.4833	15.0	1951	1981	3,950	NWS	Daily	--	--	1.23
248324	Townsend	46.3333	111.5333	11.3	1938	1992	3,840	NWS	Daily	--	--	1.09
248329	Townsend 12 ENE	46.3500	111.2833	18.0	1940	1991	5,050	NWS	Hourly	.54	.76	1.30
248363	Trident	45.9500	111.4833	12.2	1937	1992	4,040	NWS	Daily	--	--	1.20
248380	Trout Creek R S	47.8667	115.6167	29.7	1912	1992	2,360	NWS	Daily	--	--	1.65
248390	Troy	48.4833	115.9167	25.2	1961	1991	1,930	NWS	Daily	--	---	1.49
248395	Troy 18 N	48.7333	115.8833	34.9	1962	1992	2,720	NWS	Daily	--	--	1.88
248413	Turner	48.8500	108.4000	15.0	1948	1984	3,050	NWS	Daily	--	--	1.67
248430	Twin Bridges	45.5500	112.3167	9.7	1950	1992	4,630	NWS	Daily	--	--	.98
248455	Ulm 8 SE Truly	47.3500	111.4333	15.0	1949	1973	3,340	NWS	Daily	--	--	2.03
248473	Unionville	46.5500	112.0833	15.0	1950	1959	4,910	NWS	Daily	--	--	1.66
248493	Utica	46.9667	110.0833	18.0	1914	1952	4,700	NWS	Daily	--	--	1.58
248495	Utica 11 WSW	46.8833	110.3000	20.0	1962	1986	5,000	NWS	Daily	--	--	1.60
248501	Valier	48.3167	112.2500	12.1	1911	1992	3,810	NWS	Daily	--	--	1.69
248511	Vananda 5 ESE	46.3833	106.9000	15.0	1940	1991	2,700	NWS	Hourly	.77	.99	1.36
248569	Vida 6 NE	47.8667	105.4500	15.0	1948	1992	2,400	NWS	Daily	--	--	1.96
248597	Virginia City	45.3000	111.9500	16.5	1916	1992	5,760	NWS	Daily	--	--	1.14
248607	Volborg	45.8333	105.6667	14.2	1951	1992	2,980	NWS	Daily	--	--	1.65
248732	Webster 3 E	46.0667	104.1833	15.1	1953	1992	3,140	NWS	Daily	--	--	1.66
248777	Westby	48.8667	104.0500	13.6	1938	1992	2,110	NWS	Hourly	.88	1.14	1.54
248783	Western Montana BR STN	46.3333	114.0833	15.0	1965	1992	3,600	NWS	Daily	--	--	1.02
248809	West Glacier	48.5000	113.9833	29.1	1916	1992	3,150	NWS	Hourly	.55	.86	1.56
248866	West Yellowstone USFS	44.6667	111.1000	26.0	1924	1992	6,660	NWS	Hourly	.68	.97	1.24
248902	Whitefish	48.4167	114.3667	22.5	1940	1992	3,100	NWS	Daily	--	--	1.50
248927	White Sulphur Springs	46.5333	110.9167	15.0	1912	1991	5,160	NWS	Hourly	.62	.85	1.21
248930	White Sulphur Spngs 2	46.5167	110.8833	15.0	1949	1992	5,200	NWS	Daily	--	--	1.63
248933	White Sulphur Springs10N	46.6833	110.8667	15.0	1949	1978	5,440	NWS	Daily	--	--	1.27
248936	White Sulphur Spr 24 NW	46.8333	111.2000	16.0	1965	1983	4,390	NWS	Daily	--	--	1.48
248939	Whitewater	48.7667	107.6333	10.5	1951	1992	2,360	NWS	Daily	--	--	1.62

Table 1. Precipitation stations, Montana and northern Wyoming, and pertinent station information (Continued)

Station no.	Name	Latitude, in decimal degrees	Longitude, in decimal degrees	Mean annual precipitation, in inches	Period of station record used in analysis		Elevation, in feet above sea level	Agency	Type of gage	Mean storm depth, in inches, for indicated duration, in hours		
					Begin date	End date				2	6	24
248957	Wibaux 2 E	46.9833	104.1500	13.9	1946	1992	2,670	NWS	Daily	--	--	1.79
249008	Willow Creek	45.8167	111.6500	11.0	1965	1988	4,160	NWS	Hourly	.49	.72	1.16
249018	Wilsall	46.0000	110.6667	16.0	1950	1969	5,050	NWS	Daily	--	--	1.17
249023	Wilsall 8 ENE	46.0333	110.5000	20.6	1957	1992	5,840	NWS	Daily	--	--	1.65
249047	Winnett 5 NNE	47.0667	108.3167	15.0	1943	1971	2,920	NWS	Daily	--	--	1.48
249052	Winnett 8 ESE	48.9500	108.1833	15.0	1940	1991	2,850	NWS	Hourly	.76	1.03	1.47
249067	Wisdom	45.6167	113.4500	11.3	1938	1992	6,060	NWS	Hourly	.41	.58	.94
249082	Wise River 3 WNW	45.8000	113.0000	11.4	1946	1992	5,730	NWS	Daily	--	--	1.04
249111	Wolf Point 5 ESE	48.0833	105.5333	13.0	1942	1992	1,990	NWS	Daily	--	--	1.74
249175	Wyola	45.1000	107.4333	17.1	1932	1992	3,770	NWS	Daily	--	--	1.58
249211	Yellowstone PK NE ENT	45.0000	110.0000	30.0	1940	1992	7,350	NWS	Hourly	.42	.75	1.14
249240	Yellowtail Dam	45.3167	107.9333	18.9	1949	1992	3,310	NWS	Hourly	.72	1.06	1.89
249900	Zortman	47.9167	108.5333	20.0	1966	1992	3,870	NWS	Hourly	.76	1.16	2.41
480200	Alva 5 SE	44.6500	104.3500	22.8	1949	1985	4,390	NWS	Daily	--	--	2.00
480380	Arvada 3 N	44.6900	106.1000	11.6	1949	1970	3,680	NWS	Daily	--	--	1.50
481220	Burgess Junction	44.7600	107.5300	20.5	1961	1991	8,040	NWS	Daily	--	--	1.52
481775	Clark 7 NE	44.9800	109.0800	7.5	1962	1992	4,030	NWS	Daily	--	--	1.18
481816	Clearmont 2 SW	44.5800	106.4500	13.9	1950	1992	4,060	NWS	Daily	--	--	1.54
481840	Cody	44.5500	109.0600	9.7	1915	1992	4,990	NWS	Daily	--	--	1.14
481905	Colony 1 SE	44.9300	104.2000	15.2	1915	1992	3,550	NWS	Daily	--	--	1.71
482135	Crandall Creek	44.9000	109.6600	15.2	1949	1977	6,600	NWS	Daily	--	--	1.36
482415	Deaver	44.8800	108.6000	5.5	1951	1992	4,100	NWS	Daily	--	--	1.09
482466	Devils Tower 2	44.5800	104.7000	17.2	1959	1991	3,860	NWS	Daily	--	--	1.86
483770	Garland	44.7800	108.6600	4.9	1940	1966	4,250	NWS	Hourly	.39	.57	.78
484411	Heart Mountain	44.6800	108.9500	8.3	1950	1992	4,790	NWS	Daily	--	--	1.15
484760	Hulett	44.6800	104.6000	16.6	1949	1992	3,760	NWS	Daily	--	--	1.78
485345	Lake Yellowstone	44.5500	110.3900	19.5	1940	1991	7,760	NWS	Hourly	.40	.65	1.01
485355	Lamar Ranger STN	44.9000	110.2300	13.5	1949	1975	6,470	NWS	Daily	--	--	1.01
485506	Leiter 9 N	44.8500	106.2800	14.8	1965	1992	4,200	NWS	Daily	--	--	1.45
485770	Lovell	44.8300	108.3900	6.7	1949	1992	3,840	NWS	Daily	--	--	.93

Table 1. Precipitation stations, Montana and northern Wyoming, and pertinent station information (Continued)

Station no.	Name	Latitude, in decimal degrees	Longitude, in decimal degrees	Mean annual precipitation, in inches	Period of station record used in analysis		Elevation, in feet above sea level	Agency	Type of gage	Mean storm depth, in inches, for indicated duration, in hours		
					Begin date	End date				2	6	24
487079	Parkman 5 WNW	44.9800	107.4300	19.2	1952	1981	4,200	NWS	Daily	--	--	2.03
487380	Powell	44.7500	108.7600	6.1	1915	1980	4,380	NWS	Daily	--	--	.91
487545	Recluse	44.7500	105.7000	13.3	1940	1991	4,150	NWS	Hourly	.87	1.05	1.36
488124	Shell 1 W	44.5500	107.8000	10.2	1960	1992	4,230	NWS	Daily	--	--	1.28
488155	Sheridan WB AP	44.7600	106.9600	14.7	1940	1991	3,940	NWS	Hourly	.66	.99	1.63
488160	Sheridan Field STN	44.8500	106.8600	15.3	1920	1992	3,800	NWS	Daily	--	--	1.76
489025	Tower Falls	44.9100	110.4100	16.5	1949	1992	6,270	NWS	Daily	--	--	1.19
489580	Weston 3 N	44.6300	105.3100	12.3	1954	1992	3,530	NWS	Daily	--	--	1.57
489905	Yellowstone Park	44.9600	110.7000	15.5	1949	1992	6,200	NWS	Daily	--	--	1.13

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