NOAA Atlas 14

Precipitation-Frequency Atlas of the United States

Volume 4 Version 2.0:
Hawaiian Islands

Sanja Perica, Deborah Martin, Bingzhang Lin, Tye Parzybok, David Riley, Michael Yekta, Lillian Hiner, Li-Chuan Chen, Daniel Brewer, Fenglin Yan, Kazungu Maitaria, Carl Trypaluk, Geoffrey M. Bonnin

U.S. Department of Commerce

National Oceanic and Atmospheric Administration

National Weather Service

Silver Spring, Maryland, 2009

NOAA Atlas 14

Precipitation-Frequency Atlas of the United States

Volume 4 Version 2.0:
Hawaiian Islands

Sanja Perica, Deborah Martin, Bingzhang Lin, Tye Parzybok, David Riley, Michael Yekta, Lillian Hiner, Li-Chuan Chen, Daniel Brewer, Fenglin Yan, Kazungu Maitaria, Carl Trypaluk, Geoffrey M. Bonnin

U.S. Department of Commerce

National Oceanic and Atmospheric Administration

National Weather Service

Silver Spring, Maryland, 2009

Library of Congress Classification Number
G1046
.C8
U6
no.14
v.4
(2009)

Table of Contents

1. Abstract

NOAA Atlas 14 contains precipitation frequency estimates for the United States with associated 90% confidence intervals and supplementary information on temporal distribution of heavy precipitation, seasonality, trend in annual maximum series data, etc. It includes pertinent information on development methodologies and intermediate results. The results are published through the Precipitation Frequency Data Server - PFDS (http://hdsc.nws.noaa.gov/hdsc/pfds).

The Atlas is divided into volumes based on geographic sections of the country. The Atlas is intended as the official documentation of precipitation frequency estimates and associated information for the United States.

2. Preface to Volume 4

NOAA Atlas 14 Volume 4 contains precipitation frequency estimates for the Hawaiian Islands. The Atlas supercedes precipitation frequency estimates published in Technical Paper No. 43, "Rainfall-Frequency Atlas of the Hawaiian Islands for Areas to 200 Square Miles, Durations to 24 Hours, and Return Periods from 1 to 100 Years" (U.S. Weather Bureau, 1962) and Technical Paper No. 51, "Two- to Ten-Day Rainfall for Return Periods of 2 to 100 Years in the Hawaiian Islands" (U.S. Weather Bureau, 1965). The updates are based on more recent and extended data sets, currently accepted frequency approaches, and improved spatial interpolation and mapping techniques.

The work was performed by the Hydrometeorological Design Studies Center within the Office of Hydrologic Development of the National Oceanic and Atmospheric Administration's National Weather Service. Funding for the work was provided by NOAA National Weather Service, the U.S. Army Corps of Engineers, and the University of Hawaii. Any use of trade names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Citation and version history. This documentation and associated artifacts such as maps, grids, and point-and-click results from the PFDS, are part of a whole with a single version number and can be referenced as:

Perica, S., D. Martin, B. Lin, T. Parzybok, D. Riley, M. Yekta, L. Hiner, L.-C. Chen, D. Brewer, F. Yan, K. Maitaria, C. Trypaluk, G. M. Bonnin (2009). NOAA Atlas 14, Volume 4, Version 2.0: *Precipitation-Frequency Atlas of the United States, Hawaiian Islands*. NOAA, National Weather Service, Silver Spring, MD.

The version number has the format P.S where P is a primary version number representing a number of successive releases of primary information. Primary information is essentially the data. S is a secondary version number representing successive releases of secondary information. Secondary information includes documentation and metadata. S reverts to zero (or nothing; i.e., Version 2 and Version 2.0 are equivalent) when P is incremented. When new information is completed and added, such as draft documentation, without changing any prior information, the version number is not incremented.

The primary version number is stamped on the artifact or is included as part of the filename where the format does not allow for a version stamp (for example, files with gridded precipitation frequency estimates). All site-specific output from the PFDS is stamped with the version number and date of download.

Several versions of the project may be released. Table 2.1 lists the version history associated with the NOAA Atlas 14 Volume 4 precipitation frequency project and indicates the nature of changes made. If major discrepancies are observed or identified by users, a new release may be warranted.

Table 2.1. Version history of the NOAA Atlas 14 Volume 4.

Version no.	**Date**	**Notes**
Version 1.0	September 22, 2008	Draft data used in peer review
Version 2.0	March 30, 2009	Data released
Version 2.0	May 29, 2009	Final documentation released

3. Introduction

3.1. Objective

NOAA Atlas 14 Volume 4 provides precipitation frequency estimates for the Hawaiian Islands. The Atlas provides precipitation frequency estimates for 5-minute through 60-day durations at average recurrence intervals of 1-year through 1,000-year. The estimates were computed using an L-moment based regional frequency analysis of annual maximum series and then converted to partial duration series results. The information in NOAA Atlas 14 Volume 4 supersedes precipitation frequency estimates contained in Technical Paper No. 43, "Rainfall-Frequency Atlas of the Hawaiian Islands for Areas to 200 Square Miles, Durations to 24 Hours, and Return Periods from 1 to 100 Years" (U.S. Weather Bureau, 1962) and Technical Paper No. 51, “Two- to Ten-Day Rainfall for Return Periods of 2 to 100 Years in the Hawaiian Islands” (U.S. Weather Bureau, 1965). The results are provided at high spatial resolution and include confidence limits for the estimates. The Atlas includes temporal distributions designed for use with the precipitation frequency estimates (Appendix A.1) and seasonal information for annual maxima (Appendix A.2). In addition, the potential effects of climate change on annual maxima were examined (Appendix A.3).

The new estimates are based on improvements in three primary areas: denser data networks with longer periods of record, the application of regional frequency analysis using L-moments for selecting and parameterizing distribution functions and new techniques for spatial interpolation and mapping. The new techniques for spatial interpolation and mapping account for topography and have allowed significant improvements in areas of complex terrain.

3.2. Approach and deliverables

The approach used in this project for calculating precipitation frequency estimates largely follows the index-flood regional frequency analysis approach based on the L-moment statistics described in Hosking and Wallis (1997). This section provides an overview of the approach; greater detail is provided in Section 4.

The annual maximum series (AMS) used in the precipitation frequency analysis were extracted from precipitation measurements recorded at daily, hourly and n-minute time intervals from various sources using extraction rules described in Section 4.3.2. The data were carefully screened for erroneous measurements. The 1-day and 1-hour annual maximum series were also analyzed for potential trends (Appendix A.3).

To support the regional frequency analysis approach, homogeneous regions were initially determined based on cluster analysis. They were then tested for homogeneity using statistical measures. Individual stations in each region were also tested statistically for discordancy with other stations in the same region. Adjustments were made in the definition of regions based on underlying climatology in cases where homogeneity and discordancy criteria were not met.

A variety of distribution functions were examined for each region and duration and the most appropriate distribution was selected using a goodness-of-fit test based on the L-moments.

Precipitation frequency estimates (quantiles) for a selected distribution were determined based on the mean of the annual maximum series at the station and the regionally determined higher order L-moments at each station and for each duration. Due to the small number of stations recording data at less than 60-minute intervals, precipitation frequency estimates for durations below 60-minutes (n-minute durations) were computed using an average ratio between the n-minute and 60-minute estimates as determined based on available n-minute stations.

For the first time, the National Weather Service is providing confidence intervals for the precipitation frequency estimates in the area covered by NOAA Atlas 14. Monte Carlo simulation was used to produce upper and lower bounds of the 90% confidence intervals.

Gridded estimates of precipitation magnitude-frequency relationships and 90% confidence intervals were determined based on the mean annual maxima grids and the regionally determined higher order L-moments. Since L-moments are constant for each region, that may result in discontinuities in the quantiles at regional boundaries. In order to avoid potential discontinuities and to achieve an effective spatial interpolation of quantiles between observing stations, the AMS means at each station and for each duration were spatially interpolated using PRISM methodology developed by the PRISM Group at Oregon State University (Appendix A.4). Because the mean was derived directly at each observing station from the data series and independently of the regional computations, it was not subject to the same discontinuities. The grid of quantiles for each successive average recurrence interval was then derived in an iterative process using the Cascade, Residual Add-Back (CRAB) spatial interpolation procedure (Section 4.6). The resulting set of grids were examined and adjusted in cases where inconsistencies occurred between durations and frequencies.

Both the spatial interpolation and the point estimates were subject to external peer reviews (see Section 6 and Appendix A.5). Based on the results of the peer review, adjustments were made where necessary.

Temporal precipitation patterns, presented in probabilistic terms, were extracted for selected durations for use with the precipitation frequency estimates presented in the Atlas (Appendix A.1).

The seasonality of heavy precipitation for selected durations is represented in seasonal exceedance graphs. The graphs were developed for each region by tabulating the number of events exceeding the precipitation frequency estimate at each station for a given annual exceedance probability and duration (Appendix A.2).

NOAA Atlas 14 Volume 4 precipitation frequency estimates for any location in the Hawaiian Islands are available for download in a variety of formats via the Precipitation Frequency Data Server (PFDS) at http://hdsc.nws.noaa.gov/hdsc/pfds (via a point-and-click interface). The additional types of results and information found there include:

- cartographic maps of precipitation frequency estimates for selected frequencies and durations (available also as GIS shapefiles);
- ArcInfo ASCII grids of precipitation frequencies and associated confidence intervals for a range of durations and frequencies;
- annual maximum series used in the analysis;
- temporal distributions of heavy precipitation for selected durations;
- seasonal exceedance graphs (counts of events that exceed precipitation magnitudes) for selected annual exceedance probabilities and selected durations;
- associated Federal Geographic Data Committee-compliant metadata.

Cartographic maps were created to serve as visual aids and, unlike in Technical Papers 43 and 51, are not recommended for estimating precipitation frequency estimates. Users are urged to take advantage of the Precipitation Frequency Data Server or the underlying ArcInfo ASCII grids for obtaining point or areal frequency estimates.

4. Precipitation frequency analysis

4.1. Project area description

The project area (Figure 4.1.1) includes the eight largest islands at the southeastern end of the Hawaiian Islands archipelago. These islands are (from the northwest to southeast): Niihau, Kauai, Oahu, Molokai, Lanai, Kahoolawe, Maui, and Hawaii. In this project, the island names are spelled without the separator (or 'okina). The island of Hawaii is by far the largest, and is often called the "Big Island" to avoid confusion with the state as a whole.

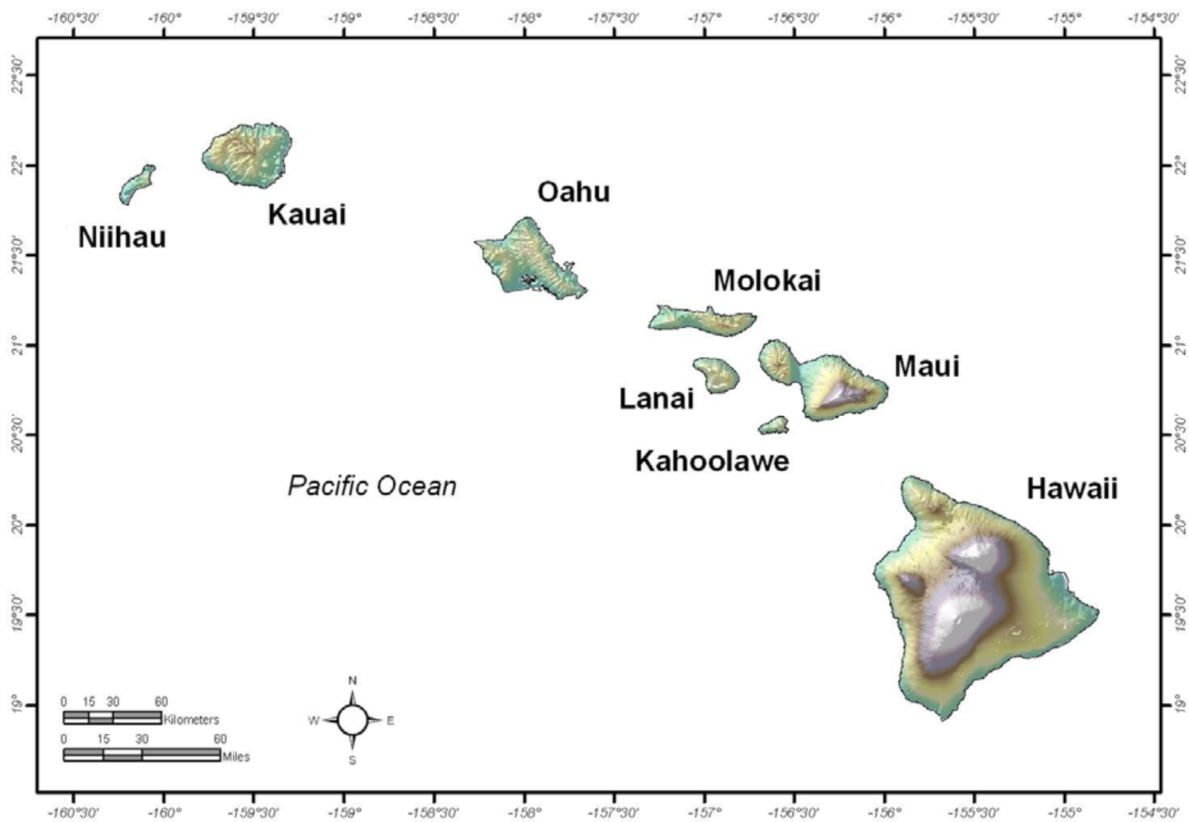


Figure 4.1.1. Project area for NOAA Atlas 14 Volume 4.

Climatology of extreme precipitation. Extreme precipitation over the Hawaiian Islands is a well-documented phenomenon with several locations on the islands holding U.S. precipitation records at longer durations. A combination of Pacific moisture with rapidly changing topography provides a wide range of precipitation in relatively short distances. Two distinct seasons are recognized in the regime of Hawaii: a summer season of five months (May through September) and a winter season of seven months (October through April). Summer is the drier season in terms of average monthly rainfall, except on the Kona Coast (leeward coast) of the Big Island. During this season, the most prominent dynamic mechanism is the easterly trade winds being forced upslope leading to orographically enhanced rainfall on nearly every island's eastern mountain range. The highest elevations on the islands, such as Mauna Kea and Mauna Loa on the Big Island, are too high to be affected by the trade winds and are some of the driest locations in Hawaii. An inversion on the upper boundary of the trade winds prevents the moist, unstable air from reaching these higher elevations. As a result, moisture flow is redirected around the higher peaks leading to extreme precipitation on either side. The leeward sides of the mountains are protected from the trade winds and are less prone to the frequent precipitation events. However, occasionally land-sea circulations are strong enough to trigger rainfall there enhanced by the topography.

Major storms and torrential rains occur most frequently in the winter season between October and April, during which the trade winds retreat south of Hawaii. These events are primarily associated with Kona lows, cold fronts, and tropical storms or hurricanes. Kona lows are subtropical cyclones that form during the cool season and usually occur two or three times a year and may affect the islands for several days. Cold fronts are more frequent (as many as six to eight may sweep across the islands, especially in the northern islands), but do not last as long as the Kona storms. Hurricanes and tropical storms are less common than Kona lows, but are similar in that they do not approach from one common direction. Unlike cold fronts and Kona storms, hurricanes and tropical storms are not limited to the winter season. They are likely to occur during the last half of the year, from July through December. With the exception of the cold fronts, storms take various paths across the islands bringing heavy rainfall to any portion of the islands. These storms provide interior and leeward locations along mountain sides with the opportunity for significant rainfall.

4.2. Data

4.2.1. Data sources

The annual maximum series used in the precipitation frequency analysis were extracted from precipitation measurements recorded at daily, hourly and n-minute time intervals from various sources. The National Weather Service (NWS) Cooperative Observer Program's daily and hourly stations obtained from National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC) were the primary data source. Table 4.2.1 shows all data sources, grouped based on the data reporting intervals (data type), with links to web sites from which the data were downloaded when applicable. The table also includes the total number of stations obtained from each source and final number of stations used in the project after some stations were merged and after screening for sufficient number of years of data and data quality (see Sections 4.2.2. and 4.4). More information on stations used in this project is given in Appendix 6. The tables in the Appendix are organized by data type and for each station include its identification number, name, state, island name, data source, latitude, longitude, elevation, period of record and regional assignment needed for regional frequency analysis (see Section 4.5.2). Locations of daily stations used in the project are shown in Figure 4.2.1 and locations of hourly and n-minute stations are shown in Figure 4.2.2. Also shown in the figures are "supplemental stations" used in to anchor spatial patterns during interpolation (see Sections 4.5.3 and 4.6).

Table 4.2.1. Data sources with data set names grouped by data reporting interval, with links to web sites from which the data were downloaded when applicable (web links as of May 2009). The table includes the total number of stations obtained from each source and final number of stations used in the frequency analysis.

Reporting time	Source of data: data set name (web link for data download)	Number of stations	
		total	used
1-day	NCDC: *TD3200* and *TD 3206* (http://cdo.ncdc.noaa.gov/CDO/dataproduct)	560	263
	Hawaii State Climate Office: monthly maxima	236	89
	Haleakala National Park & Biological Res. Division: *HaleNet* (http://webdata.soc.hawaii.edu/climate/HaleNet/Index.htm)	11	1
1-hour	NCDC: *TD3240* (http://cdo.ncdc.noaa.gov/CDO/dataproduct)	143	71
	Western Region Climate Center: *RAWS* (http://www.raws.dri.edu/index.html)	3	0
	Haleakala National Park & Biological Res. Division: *HaleNet* (http://webdata.soc.hawaii.edu/climate/HaleNet/Index.htm)	11	1
15-min	NCDC: *TD 3260* (http://cdo.ncdc.noaa.gov/CDO/dataproduct)	98	0
	NWS, Honolulu Forecast Office: *Hydronet* http://www.prh.noaa.gov/hnl/hydro/hydronet/hydronet-data.php	70	0
	United States Geological Survey	10	0
n-min	NCDC: 5-min to 180-min monthly maxima from *TD9649* and 1973 – 1979 datasets and Automated Surface Observing System (ASOS) 1-min data beginning in 1998.	4	3

4.2.2. Initial data screening

Geospatial data. Latitude, longitude and elevation data for all stations used in the project were screened for errors. In a few cases, it was necessary to re-locate stations that plotted in the ocean or were severely mismatched according to elevation differences with a digital elevation model. Changes to coordinates were kept to a minimum. One station was deleted because its proper location could not be identified. The tables in Appendix 6 contain the coordinates used in this project.

Station merging. Stations in the project area within 1.5 miles in horizontal distance and 500 feet in elevation with records that contained an overlap of 5 years or less in their records or a gap between records of 5 years or less were considered for merging to increase record lengths and reduce spatial overlaps. The statistical t-test (at the 90% confidence level) was used to ensure that the annual maximum series of stations that were candidates for merging were from the same population and appropriate to be merged. Forty-two sets of daily stations (either in pairs or sets of three) and ten sets of hourly stations that passed the t-test were merged. Station metadata shown in Appendix 6 is after merging was completed.

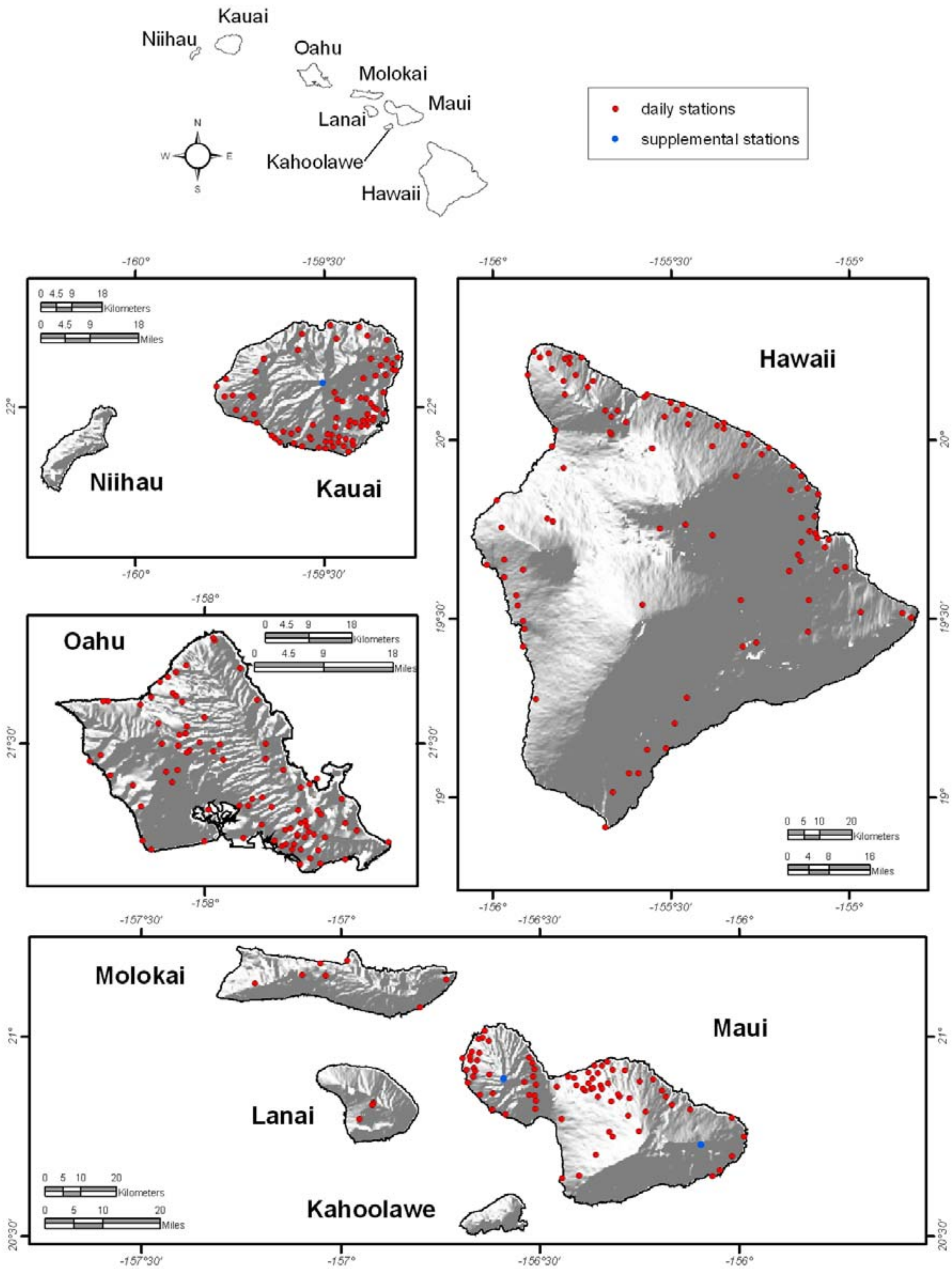


Figure 4.2.1. Map of daily and supplemental daily stations for NOAA Atlas 14 Volume 4.

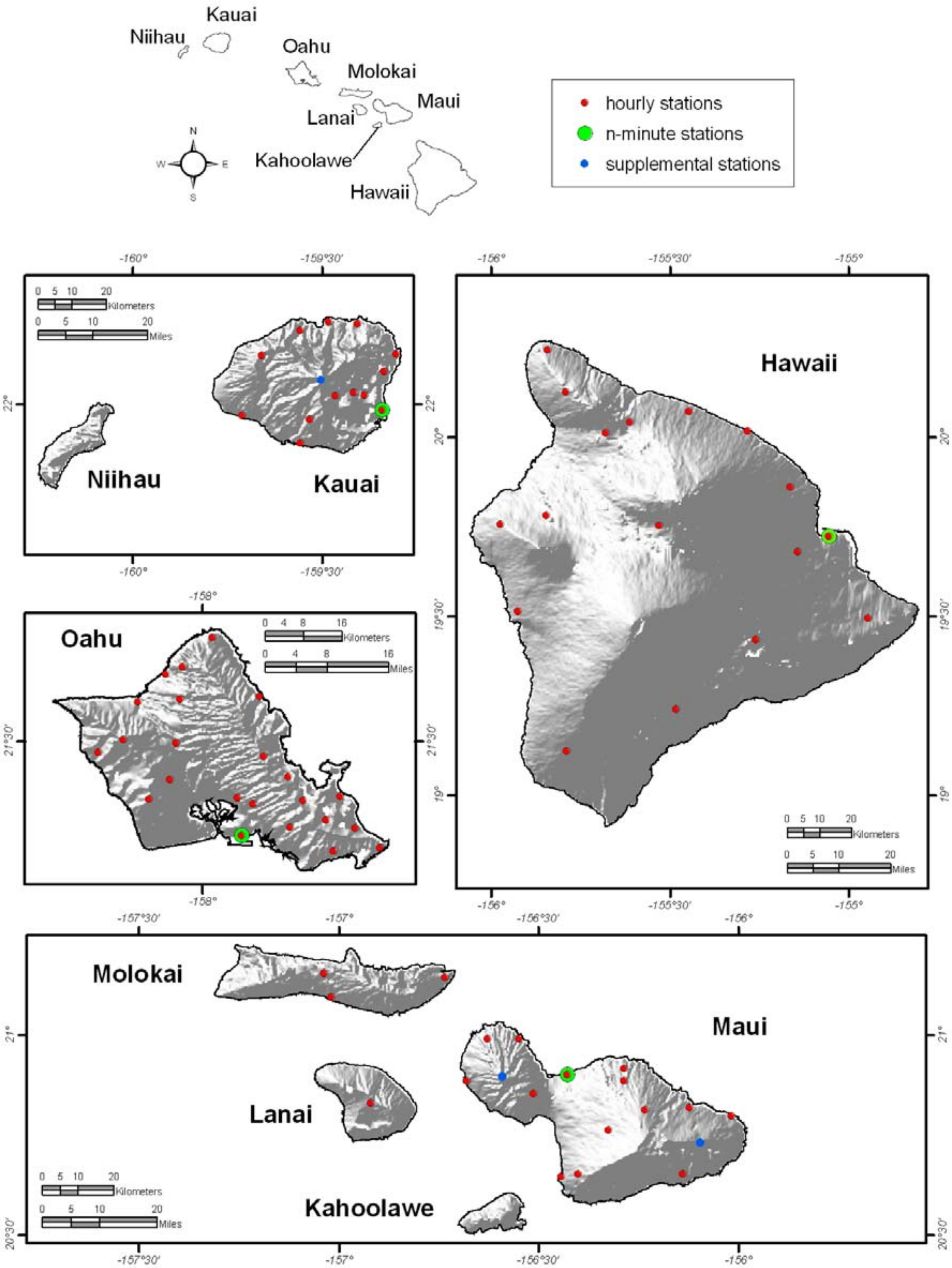


Figure 4.2.2. Map of hourly, supplemental hourly and n-minute stations for NOAA Atlas 14 Volume 4.

4.3. Annual maximum series extraction

4.3.1. Series selection

Precipitation frequency estimates can be obtained by analyzing annual maximum series (AMS) or partial duration series (PDS). AMS are constructed by taking the highest accumulated precipitation for a particular duration in each successive year of record, whether the year is defined as a calendar or water year. Water year, starting on October 1 and ending on September 30 was used in this Atlas. AMS inherently exclude other extreme cases that occur in the same year, regardless of whether those extreme cases exceed maxima of other years. PDS include all amounts for a specified duration at a given station above a pre-defined threshold regardless of year and can include more than one event in any particular year. Differences in magnitudes of corresponding frequency estimates from the two series are negligible for exceedance probabilities of up to about 10%, but differ at other probabilities (see Section 4.5.1 for more details). This difference can be important depending on the application. Because PDS can include more than one event in any particular year, the results from a PDS analysis are thought to be more useful for designs based on more frequent events.

In this project, only AMS were directly extracted from the data. AMS-based precipitation frequency estimates where then converted to PDS-based frequency estimates using Langbein's empirical formula (see Sections 4.5.1 and 4.5.4). The AMS were extracted at each station for a range of durations varying from 5 minutes to 60 days. AMS for the 24-hour duration were compiled from daily and hourly records; 2-day through 60-day AMS were compiled only from daily records. Hourly data were also used to compile AMS for 60-minute through 12-hour durations. Stations from the Hawaii State Climate Office database with only monthly maxima were used to compile AMS for the 24-hour duration only. AMS for durations from 5-minute to 60-minute were compiled from n-minute datasets.

4.3.2. Criteria for extraction

The procedure for developing an AMS from a dataset employs specific criteria designed to extract only reasonable maxima if a year is incomplete or has accumulated data. Accumulated data occurred in some daily records where observations were not taken daily, so recorded numbers represent accumulated amounts over extended periods of time. Since the precipitation distribution over the period is unknown, the total amount was distributed equally among the days of the accumulated series during the extraction process for consideration as maxima. All annual maxima that resulted from accumulated data were flagged and went through additional screening to ensure that the incomplete data did not result in erroneously low maxima (see Section 4.4.2).

The criteria for AMS extraction used in this project was designed to exclude maxima if there were too many missing or accumulated data during the year and more specifically during critical months when rainfall maxima were most likely to occur ("wet season"). The wet seasons were assigned by assessing histograms of annual maxima. The final wet seasons were allocated based on homogeneous regions developed for frequency analysis. The development and delineation of the homogeneous regions for frequency analysis is discussed in Section 4.5.2 and shown in Figures 4.5.1 and 4.5.2. Wet seasons assigned to daily and hourly regions are shown in Tables 4.3.1 and 4.3.2, respectively.

Table 4.3.1. Wet season for each of the 28 daily regions.

Daily region	Wet season
5, 17, 19, 20, 21, 22	October - April
4, 6, 7, 14, 18, 26, 27	October - May
23, 24	October - September
9	September - May
8, 10, 11, 16, 28	August - April
1, 2, 12, 13	August - May
15	July - April
3, 25	November - April

Table 4.3.2. Wet season for each of the 11 hourly regions.

Hourly region	Wet season
8, 9	October - April
1, 5	September - April
2, 3, 4, 7	September - May
6, 10, 11	August - May

The flowchart below (Figure 4.3.1 with Table 4.3.3) depicts the AMS extraction criteria for all durations. Various thresholds for acceptable amounts of missing or accumulated data were applied to the year and wet season based on duration. For example, regarding accumulations for the 10-day duration, if a year had more than 66% of days with accumulated data, then the maxima for that year for 10-day duration was (conditionally) rejected. If the year had between 33% and 66% of days with accumulated data, then it was further screened by assessing the lengths of the accumulated periods. If more than 66% of the accumulated data came from accumulation periods of 7 days or more, the number was rejected. If the year had less than 33% of accumulated data, the extracted maximum was passed to another set of criteria for accumulations during its wet season, etc. The extracted maximum amount for a given year had to pass through all of the criteria in Figure 4.3.1 to be accepted. All rejected maxima were compared with the accepted maxima; if they were higher than 95% of the maxima at that station, then they were kept in the record. Also, if a 1-day observation was higher than any other accumulated amount in a year, then it was retained as a ‘true maximum’. For the 1-day duration, annual maxima were also extracted from the Hawaii State Climate Office’s datasets that contained records of only 1-day monthly maxima. Data quality flags were assigned to accepted and rejected maxima to assist in further quality control of AMS described in Section 4.4.

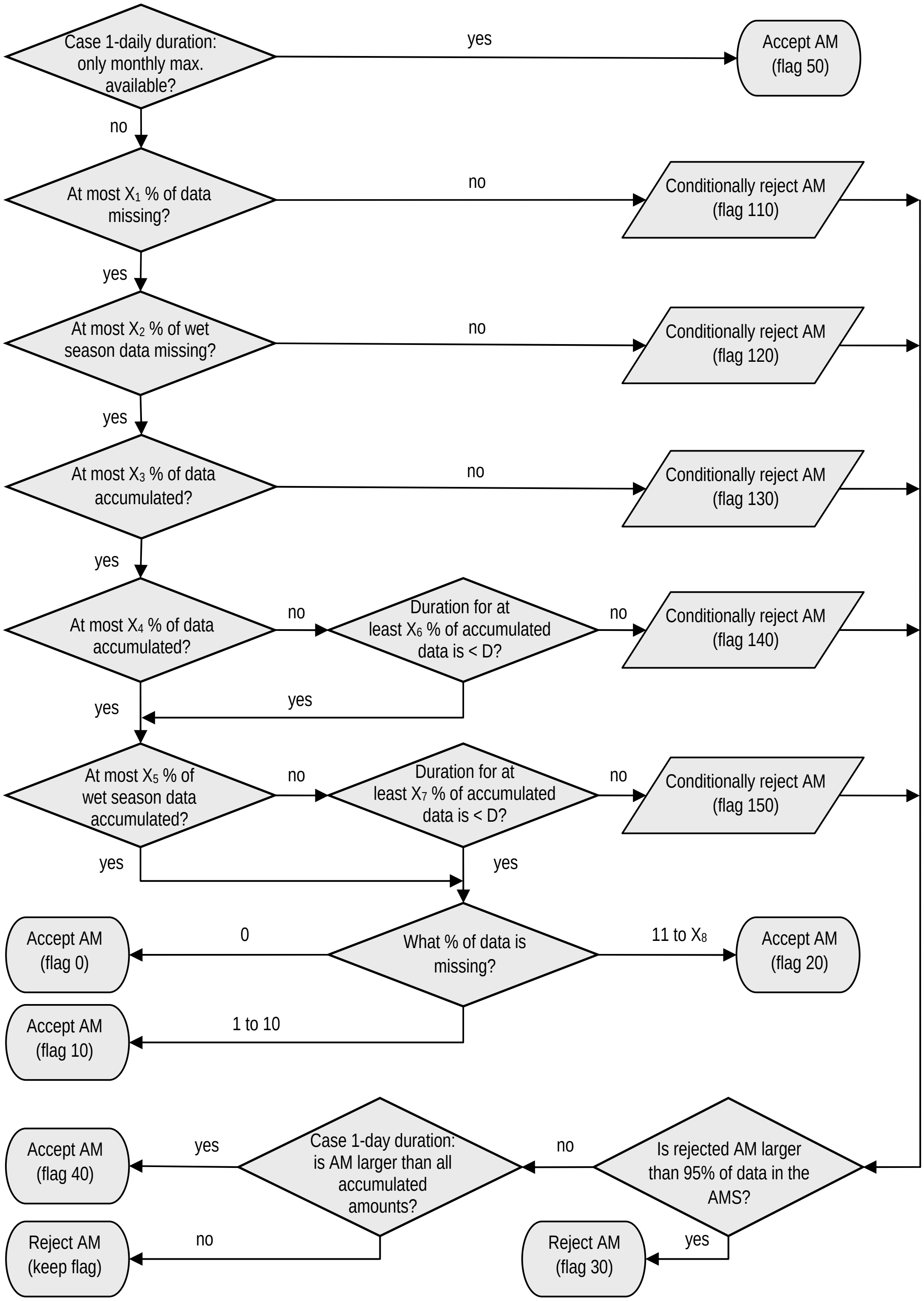


Figure 4.3.1. Flowchart depicting the criteria used to extract annual maxima from daily and hourly data. Data quality flags were assigned based on acceptance and rejection. Table 4.3.3 shows the parameter values (X_i and D) for each criterion and duration.

Table 4.3.3. Specific parameters applied during annual maximum extraction for all hourly and daily durations (as shown in Figure 4.3.1).

Parameter	Hourly durations						Daily durations								
	1	2	3	6	12	24	1	2	4	7	10	20	30	45	60
X_1, X_2 (%)	33	33	33	33	33	33	20	20	20	20	20	20	20	20	20
X_3 (%)	0	66	66	66	66	66	0	66	66	66	66	66	66	66	66
X_4 (%)	0	33	33	33	33	33	0	33	33	33	33	33	33	33	33
X_5 (%)	0	15	15	15	15	15	0	15	15	15	15	15	15	15	15
X_6, X_7 (%)	0	66	66	66	66	66	0	66	66	66	66	66	66	66	66
X_8 (%)	33	33	33	33	33	33	20	20	20	20	20	20	20	20	20
D (hours or days)	1	2	3	5	8	14	1	2	4	6	7	12	15	18	18

4.4. AMS screening and quality control

4.4.1. Record length (data years)

In this project, record length is characterized by the number of years for which annual maxima could be extracted (data years) rather than the entire period of record. Only daily stations with 20 or more data years and hourly stations with 15 or more data years were used in the precipitation frequency analysis. Record lengths for daily stations varied between 20 and 100 with an average of 44 data years and a median of 38 data years (Table 4.4.1). Three additional daily stations (supplemental stations) with less than 20 years of data were retained in the dataset to assist in spatial interpolation process (see Section 4.6). The record lengths of the hourly stations varied between 15 and 43, with 32 data years on average and a median of 35 data years. Three of the four available n-minute records had more than 15 years of data, with an average of 20 data years. Figure 4.4.1 shows the number of stations within given ranges of data years for the daily (24-hour) and hourly (1-hour) data. The number of stations and the number of data years for longer daily durations may vary due to accumulated data. The records for all durations extended through December 2005.

Table 4.4.1. Record length statistics for daily, hourly, and n-minute stations used in the analysis.

Station type	Number of stations	Record length (data years)			
		minimum	average	median	maximum
daily	337	20	44	38	100
hourly	71	15	32	35	43
n-minute	3	17	20	18	25

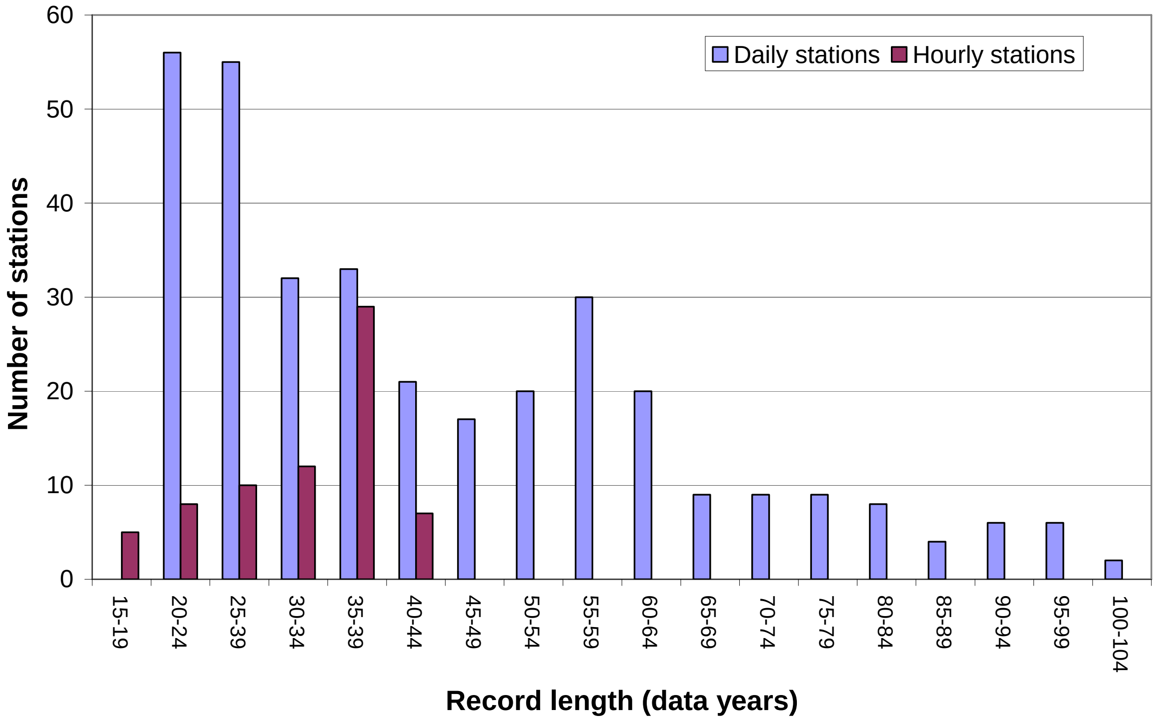


Figure 4.4.1. Number of daily and hourly stations used for precipitation frequency analysis grouped by record length.

4.4.2. Outliers

For this project, outliers are defined as annual maxima that are significantly lower or higher than the majority of maxima at a given station for a given duration. Since data at both high and low extremities can considerably affect precipitation frequency estimates, they have to be carefully investigated and either corrected or removed from the AMS if due to measurement errors. Statistical tests for outliers, similar to tests used for the detection of outliers in flood frequency analysis in Bulletin 17B, "Guidelines for Determining Flood Flow Frequency" (Interagency Advisory Committee on Water Data, 1982), were used to identify low and high outliers for all durations. In addition, for 1-hour and 24-hour durations, all values above frequency estimates corresponding to a 1% exceedance probability in the project area were also flagged as high outliers.

Further examination of low outliers indicated that almost all of them were from years with significant percent of missing and/or accumulated data. They were presumed untrue maxima and were removed from the datasets. All values identified as high outliers were mapped with concurrent measurements taken at nearby stations. Values that were recommended for further investigation were then checked against original records, climatological bulletins, and/or local expertise at the National Weather Service Forecast Office in Hawaii. Depending on the outcomes of investigation, the values were kept in the dataset, corrected and kept, or removed from the datasets.

4.4.3. Inconsistencies across durations

Annual maxima were compared across durations for each year. Because quite a few stations in this project had significant number of missing and/or accumulated data, there were cases where extracted shorter duration annual maxima were greater than corresponding longer duration annual maxima. In those cases, shorter duration precipitation amounts were used to replace annual maxima extracted for longer durations.

Co-located stations. 1-day/24-hour AMS at co-located daily and hourly stations were compared for overlapping periods of record. Where corresponding AMS were significantly different, efforts were made to identify source of error and to correct erroneous observations across all durations that may be affected. Also, whenever hourly stations had longer period of record than their co-located daily station, daily data series were accordingly extended.

4.4.4. AMS correction factors for constrained observations

Daily durations. The majority of daily AMS data used in this study comes from daily stations at which readings were taken once every day (constrained observations). Due to the fixed beginning and ending of observation time at daily stations, it is likely that extracted (constrained) annual maxima were lower than the true (unconstrained) maxima. To account for the likely failure of capturing the true-interval 24-hour maxima, correction factors were applied to AMS extracted from data recorded at daily stations. The correction factors for this project were computed using 32 co-located daily and hourly stations in the project area with at least 15 years of overlapping period. Slope coefficients of zero-intercept regression models of concurrent (occurring within +/- 1 day) unconstrained and constrained annual maxima for a given duration were used to estimate correction factors. Correction factors for all daily durations are given in Table 4.4.2. As can be seen from the table, the effects of constrained observations were negligible for durations of 4 days or more.

Table 4.4.2. Correction factors applied to AMS extracted from daily stations.

Duration (days)	Correction factor
1	1.10
2	1.07
4 or more	1.00

Hourly durations. Similar adjustment was needed on hourly AMS data extracted from hourly stations to account for the effects of constrained ‘clock hour' to unconstrained 60-minute observations. Because there were only 4 co-located hourly and n-minute stations, the conversion factors were estimated using concurrent unconstrained and constrained monthly maxima for a given hourly duration. Correction factors applied to AMS from hourly data are given in Table 4.4.3. Correction factors for durations of 3 hours or longer were estimated to be 1.0.

Table 4.4.3. Correction factors applied to AMS extracted from hourly stations.

Duration (hours)	Correction factor
1	1.11
2	1.06
3 or more	1.00

4.4.5. AMS trend analysis

Precipitation frequency analysis methods used in NOAA Atlas 14 volumes are based on the assumption of a stationary climate over the period of observation (and application). The tests and the main findings are described in more detail in Appendix A.3. Briefly, the stationarity assumption was tested by applying a parametric t-test and non-parametric Mann-Kendal τ test for trends in the annual maximum series data at 5% significance level. Statistical tests were done on the 1-day and 1-hour AMS. Both tests identified trends in about 20% of the 1-day AMS data and no trends in 1-hour AMS. Almost all trends in the 1-day AMS were negative. The relative magnitude of any trend in AMS for a region as a whole was also assessed by linear regression techniques. AMS were rescaled by corresponding mean values and then regressed against time. The regression results were tested as a set against a null hypothesis of zero serial correlation (zero regression slopes). The null hypothesis of no trends in AMS data could not be rejected at 5% significance level. Because all tests basically indicated no (positive) trends in the data, the assumption of stationary climate was accepted for this project area and no adjustment on AMS was recommended.

4.5. Precipitation frequency estimates with confidence intervals at stations

4.5.1. Overview of methodology and related terminology

Precipitation magnitude-frequency relationships at individual stations have been computed using an **index-flood regional frequency analysis** approach based on **L-moment statistics**, as outlined by Hosking and Wallis (1997). Frequency analyses were carried out on **annual maximum series (AMS)** for the following n-minute durations: 5-min, 10-min, 15-min, and 30-min, for the following hourly durations: 1-hour, 2-hour, 3-hour, 6-hour, and 12-hour, and for the following daily durations: 1-day, 2-day, 4-day, 7-day, 10-day, 20-day, 30-day, 45-day and 60-day. AMS-based precipitation frequency estimates were then converted to **partial duration series (PDS)** based frequency estimates using an empirical formula that allows for conversion between AMS and PDS frequencies. To allow for assessment of uncertainty in estimates, 90% confidence intervals were constructed on AMS and PDS frequency curves using a simulation-based procedure described in Hosking and Wallis (1997).

Frequency analysis involves mathematically fitting an assumed distribution function to the data. Distribution functions commonly used to fit precipitation data include 3-parameter distributions such as Generalized Logistic (GLO), Generalized Extreme Value (GEV), Generalized Normal (GNO), Generalized Pareto (GPA), and Pearson type III (PE3), the 4-parameter Kappa distribution, and the 5-parameter Wakeby distribution. When fitting a distribution to a precipitation annual maximum series extracted at a given location (and selected duration), the result is a frequency distribution relating precipitation magnitude to its **annual exceedance probability (AEP)**. The inverse of the AEP is frequently referred to as the **average recurrence interval (ARI)**, also known as return period. When used with the AMS-based frequency analysis, ARI does not represent the “true” average period between exceedances of a given precipitation magnitude, but the average period between years in which a given precipitation magnitude is exceeded at least once. Those two average periods can be considerably different for more frequent events. The “true” average recurrence interval (ARI) between cases of a particular magnitude can be obtained through frequency analysis of PDS.

Differences in magnitudes of corresponding frequency estimates (i.e., **quantiles**) from the two series are negligible for ARI > 10 years, but notable at smaller ARI. Because the PDS can include more than one event in any particular year, the results from a PDS analysis are generally considered to be more useful for designs based on more frequent events (e.g., Laurenson, 1987). To avoid confusion, we use the term AEP with AMS frequency analysis and ARI with PDS frequency analysis. The term ‘frequency’ is interchangeably used to specify the ARI and AEP.

L-moments provide an alternative way for describing frequency distributions to traditional product moments (conventional moments) or maximum likelihood moments. They are well suited for analysis of precipitation data that exhibit significant skewness. Because sample estimators of L-moments are linear combination of (ranked) observations, they are less subject to bias in estimation and are less susceptible to the presence of outliers in the data than conventional moments. L-moment estimators of Generalized Extreme Value (GEV) distribution parameters (GEV is the distribution of choice in this project, see Section 4.5.3) compared favorably with parameter estimators obtained by the maximum likelihood method, especially for small to moderate sized samples (Hosking and Wallis, 1997). L-moments that are normally used to describe various frequency distributions include 1st and 2nd order L-moments: L-location (λ_1) and L-scale (λ_2), and the following L-moment ratios: L-CV (τ), L-skewness (τ_3), and L-kurtosis (τ_4). L-CV, which stands for “coefficient of L-variation”, is calculated as the ratio of L-scale to L-location (λ_2/λ_1). L-skewness and L-kurtosis are calculated as ratios of the 3rd order (λ_3) and 4th order (λ_4) L-moments to the 2nd order (λ_2) L-moment, respectively, and are therefore independent of scale.

One of the primary problems in frequency analysis is the need to provide frequency estimates for average recurrence intervals that are significantly longer than available records. The regional approach, which uses data from all stations that form a homogeneous region to obtain quantiles at a single station, has been shown to yield more accurate estimates of extreme quantiles than other approaches that use data from only a single station. The regional approach of choice for this project is the **index-flood regional frequency analysis approach**. The term 'index-flood' comes from its first applications in flood frequency analysis (Dalrymple, 1960), but the method is applicable to precipitation or any other kind of hydro-climatic data. The underlying assumption of the index-flood approach is that all stations in a homogeneous region have a common magnitude-frequency curve (**regional growth curve**) that becomes location-specific after applying a site-specific scaling factor (index flood). The scaling factor is typically the mean of the data at a given location. Accordingly, the scaling factor in this project was the mean of the annual maximum series extracted from the precipitation record for a given station and selected duration. Site-specific estimates of L-location and regional estimates of L-CV, L-skewness and L-kurtosis are used to calculate distribution parameters and quantiles. Regional values of L-moment ratios are obtained from station specific L-moment ratios weighted by record lengths. They are used to calculate quantiles of a regional dimensionless distribution, called **regional growth factors** (RGFs), for selected AEPs. Because the distribution parameters are constant for each region (for a specified duration), there is a single RGF for each region that varies only with frequency. The RGFs are then multiplied by the site-specific scaling factor to produce the quantiles at each frequency and duration for each station.

4.5.2. Delineation of homogeneous regions

Initial delineation of regions. Cluster analysis was used to initially group stations into regions. Hypothetically, regionalization could be done for each duration independently, but that could result in inconsistencies in magnitude-frequency relationships over the various durations. Given that the cluster analysis on 1-day and 10-day AMS did not show significant differences in regional boundaries, it was decided to construct a single set of regions applicable to all daily durations (daily regions). Regional groups obtained through cluster analysis were initially improved based on 1-day statistical measures, physical considerations, and climatology of extreme events. Regions were further refined based on the statistical measures obtained through analysis of longer durations.

Because there were significantly less hourly than daily stations and to avoid regions with no stations for hourly durations, regions for durations < 24 hours (hourly regions) were delineated independently. Initial hourly regions obtained through cluster analysis were refined based on 1-hour statistical measures, comparisons with daily regions, and climatology of short-term precipitation extremes. All daily and hourly regions were finalized based on consultations with local climate experts.

Initial regions were formed through cluster analysis using one of the nonhierarchical clustering methods, K-mean algorithm, because of its resistance to outliers (McQueen, 1967). Nonhierarchical clustering algorithms start with predefined clusters that can be formed randomly and then reassign the cluster membership based on the similarity between stations that is measured by the Euclidian distance in terms of the selected attribute variables (Everitt et al., 2001). The set of prospective attribute variables for daily durations included at-site values of: latitude, longitude, elevation, mean annual precipitation, mean annual maximum 24-hour precipitation, and maximum observed 24-hour precipitation. Only the latter three were used in the final clustering algorithm. Similarly, for hourly durations, the following attribute variables were selected: mean annual precipitation, mean annual maximum 1-hour precipitation, and maximum observed 1-hour precipitation. Since cluster analysis is sensitive to differences in ranges for attribute variables, all variables were transformed to make their ranges comparable before they were used in cluster analysis. There was some randomness involved in the clustering procedure. Results were sensitive to a choice of clustering method, selection of attribute variables, choice of transformation for attribute variables, etc. There was also some ambiguity on the optimal number of clusters. After several iterations, an initial set of seven daily clusters and four hourly clusters was accepted.

Refinement of regions. The daily and hourly regions delineated by the clustering procedure were investigated for heterogeneity using discordancy and heterogeneity measures, as suggested by Hosking and Wallis (1997). For daily regions, statistical measures were first investigated using 1-day data. Similarly, for hourly regions, initial homogeneity investigation was done using 1-hour data. **Discordancy measure (D)** was used to determine if a station had been inappropriately assigned to a region. The measure was calculated for each station in a region as the distance of a point in a 3-dimensional space represented by at-site estimates of three L-moment ratios (L-CV, L-skewness and L-kurtosis) from the cluster center that was defined using the unweighted average of the three L-moment ratios from all stations within the region. Stations that were flagged as discordant (D > 3) were first investigated for erroneous data in the AMS. However, since the data had already undergone quality checks, high discordancy values were more likely to indicate that a station was discordant with the rest of the stations in the region than the existence of errors in the data.

Heterogeneity measures (H) were used to judge the relative heterogeneity of a proposed region as a whole based on L-moment ratios. Heterogeneity measures compared the variability of sample estimates of L-moment ratios in a region relative to their expected variability. Expected variability of L-moments was obtained through simulations using the Kappa distribution as the underlying population distribution. The Kappa distribution includes several 3-parameter distributions as special cases, so its results are less affected by the choice of distribution. The heterogeneity measure, H1 that examines the variability of sample estimators of L-CV was used in this project to judge the relative heterogeneity in the proposed regions. H1 is generally accepted to be the most reliable among potential heterogeneity measures in discriminating between homogeneous and heterogeneous regions. A region is generally considered homogenous if H1 is less than 2.0.

An iterative modification of regions was conducted to reduce discordancy and heterogeneity measures. Several discordant stations were reassigned to different regions; several regions were redefined or divided in sub-regions. The daily regions delineated based on 1-day AMS were further refined by investigating heterogeneity measures for other daily durations. Similarly, the hourly regions delineated based on 1-hour AMS were further refined by investigating heterogeneity measures for other hourly durations.

In all cases where H1 was greater than 2.0, sensitivity tests showed that one or several stations were driving the H1 measure due to the nature of their data sampling. If omitting the offending station(s) decreased H1 significantly and changed the 100-year estimates and regional growth factors by 5% or less, then the high H1values in these cases were accepted without modifying the regions themselves.

After numerous iterations, 28 daily regions and 11 hourly regions were formed. Figure 4.5.1 shows regional groupings for daily durations. Figure 4.5.2 shows regional groupings for hourly durations. Appendix A.7 and A.8 list the regionally-averaged L-moment statistics and H1 values, respectively, for all regions and durations. All 28 daily regions were homogeneous (H1 < 2.0) with respect to the 1-day duration and the majority of other daily durations. Similarly, H1 measure was less than 2.0 for nearly all hourly regions and durations.

Station independence check. One of the assumptions in the index-flood method is that annual maxima extracted at different stations inside a homogeneous region are independent. Precipitation events, especially at longer durations, typically affect an area large enough to contain more than one station. Daily AMS data were investigated in each region for cross correlation between stations to assess inter-site dependence. Stations within a region were analyzed using a *t-test* at the 90% confidence level for correlation coefficients. Cross correlation between stations in the project area was not found to be statistically significant for a majority of cases analyzed, so it was assumed that the impact of potential station dependence on the quantiles is minimal.

4.5.3. AMS-based frequency estimates

Choice of distribution. The goodness-of-fit test based on L-moment statistics for 3-parameter distributions, as suggested by Hosking and Wallis (1997), was used to assess which of the commonly used 3-parameter distributions (GEV, GNO, GLO, GPA, PE3) provide acceptable fit to the AMS data. Although it is not required that the same type of distribution is used for each region and duration, choosing a different distribution for different durations (and/or regions) may lead to inconsistencies between frequency estimates across durations (and/or nearby stations). Therefore, the test results were also used to identify if there was any particular distribution that gave an acceptable fit to the AMS data across a majority of regions and durations. Among tested distributions, GEV and GNO gave an acceptable fit in most cases. For example, they provided acceptable fit in 23 of 28 daily regions for 1-day data and in 10 of 11 regions for 1-hour data. L-moment ratios for various regions and durations on L-kurtosis versus L-skewness plots tended to cluster around the GEV distribution more than any other distribution. Since the GEV distribution is a distribution typically used to describe precipitation data, the decision was made to adopt GEV distribution for all regions and for all durations.

Frequency estimates for daily and hourly durations. For a given daily (hourly) duration, regional estimates of L-CV, L-skewness and L-kurtosis for each of the 28 daily regions (11 hourly regions) were obtained from station specific L-moment ratios weighted by record lengths. They were used to calculate parameters of a regional dimensionless GEV distribution following formulas given in Hosking and Wallis (1997) and to calculate regional growth factors for selected AEPs (50, 20, 10, 4, 2, 1, 0.5, 0.2 and 0.1 percent). (Appendix A.9 lists the RGFs for all regions and durations.) The RGFs were then multiplied by site-specific mean annual maximum values to produce quantiles for each selected frequency and duration for all stations in the region. This calculation was repeated for all regions and for all durations.

Frequency estimates for supplemental stations. Three stations (called supplemental) located in remote areas (see Figures 4.2.1 and 4.2.2 for their locations and Table A.6.3 in Appendix A.6 for their metadata) that did not have sufficient data to be used in frequency analysis were retained primarily to assist in spatial interpolation of mean annual maxima and precipitation frequencies (see Section 4.6). The stations were assigned to appropriate daily and hourly regions. Mean annual maxima for all durations at those three locations were estimated based on available data, spatially interpolated values, and information available from Technical Papers No. 43 and No. 51. Precipitation frequency estimates for each frequency and duration were then obtained by multiplying mean annual maxima with appropriate RGFs.

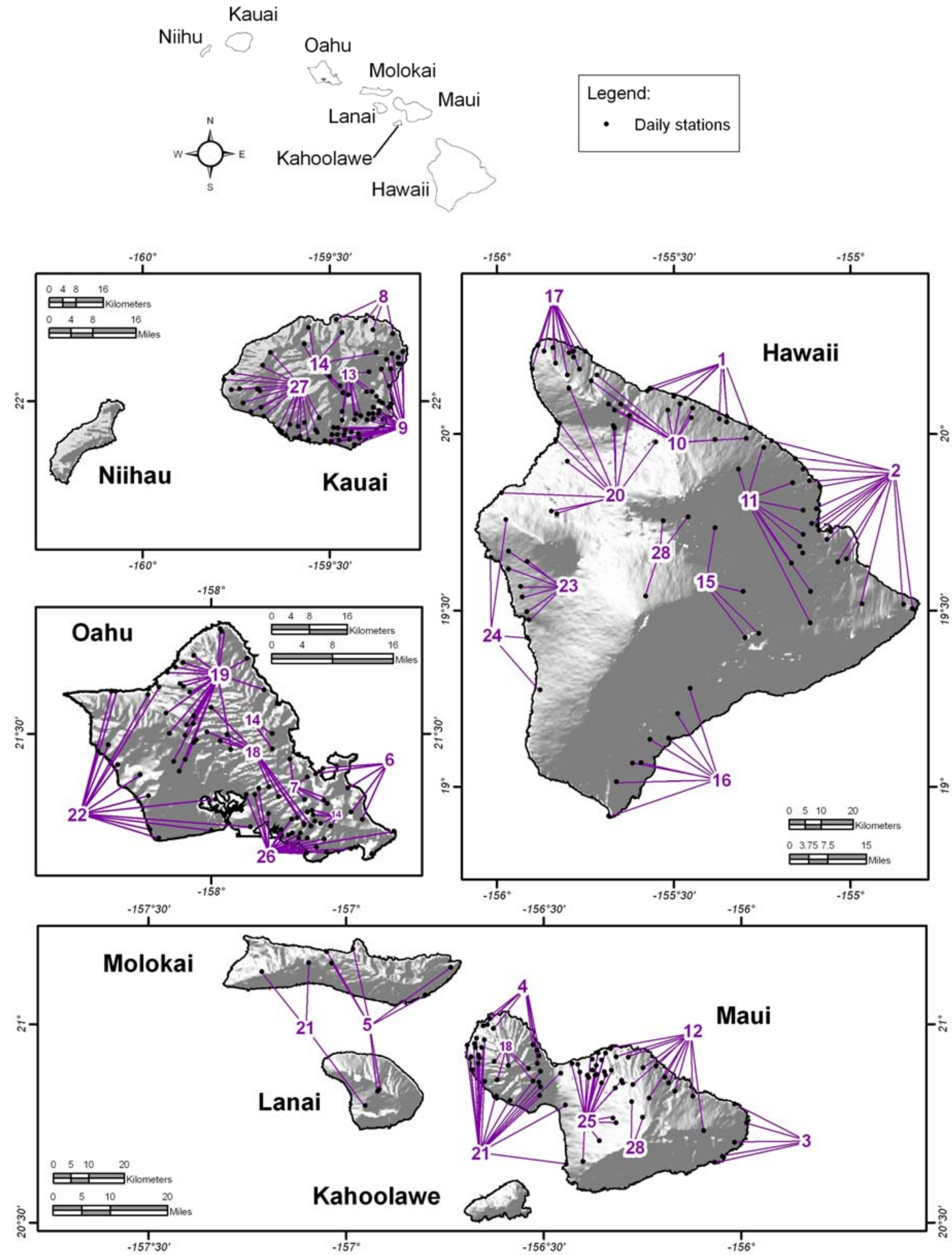


Figure 4.5.1. Station groupings for daily durations.

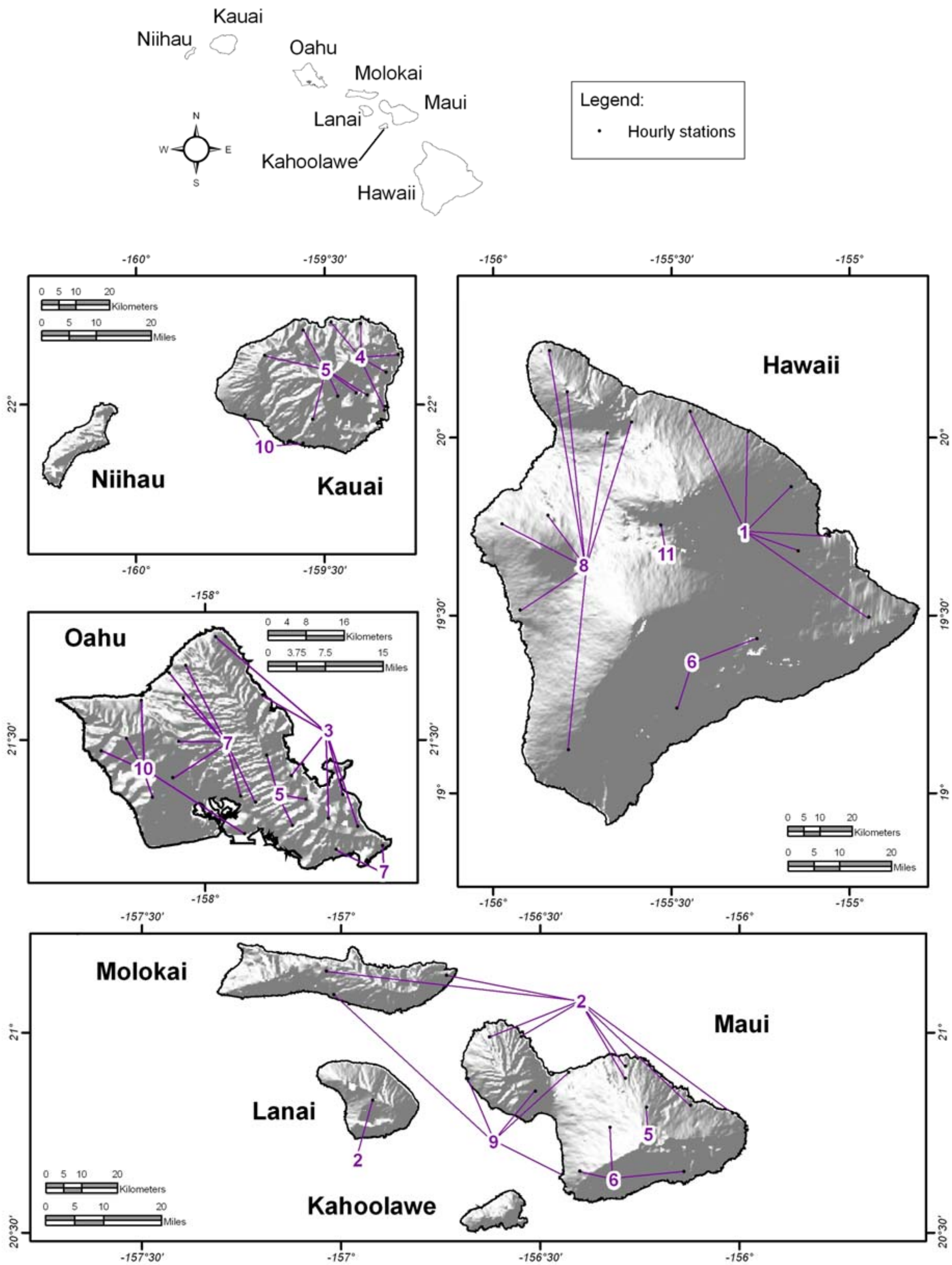


Figure 4.5.2. Station groupings for hourly durations.

Frequency estimates for n-minute durations. Because only four n-minute stations were available in the whole project area (see Figure 4.2.2 for their locations), n-minute precipitation frequencies were estimated by applying linear scaling factors to corresponding 60-minute frequencies at hourly stations. Three of the n-minute stations had at least 15 years of data and were analyzed as one region. The same regional frequency algorithm as for daily and hourly durations was used for n-minute durations. GEV distribution was, similarly, the distribution of choice. The n-minute scaling factors were calculated as the averages of ratios of n-minute quantiles for AEPs between 50% and 1% from n-minute stations and corresponding 60-minute quantiles from co-located hourly stations. These scaling factors were applied to 60-minute quantiles to estimate quantiles at n-minute durations. Table 4.5.1 shows the n-minute scaling factors used in this project.

Table 4.5.1. Scaling factors applied to 60-minute quantiles to calculate precipitation quantiles at n-minute durations.

Duration (minutes)	5	10	15	30
Scaling factor	0.27	0.37	0.47	0.69

Consistency in frequency estimates across durations. All precipitation quantiles were inspected for inconsistencies across durations. Since the quantiles at a given station were calculated independently for each duration, it could happen that quantile estimate for a given frequency was higher for a shorter duration than the next longer duration. The underlying causes for each of those irrational estimates were carefully inspected. The majority of anomalous cases were caused by data sampling variability across durations, particularly because record length at one duration was significantly shorter compared to record lengths at other durations. Some irregularity occurred at co-located stations because different regionalization was used for hourly and daily durations. Finally, there were a few cases caused by random variation of distribution parameterization between durations. Irrational frequency estimates were replaced with estimates that were assigned in proportion to frequency estimates at other durations that were judged reliable.

4.5.4. PDS-based frequency estimates

As mentioned in Section 4.3, partial duration series were not extracted from the precipitation datasets in this project. Instead, PDS-based quantiles were estimated indirectly using the Langbein's empirical formula (Langbein, 1949):

$$\mathrm{AEP} = 1 - \exp\left(-\frac{1}{\mathrm{ARI}}\right).$$

This formula transforms PDS-based average recurrence intervals to annual exceedance probabilities. PDS-based frequency estimates were calculated for the same durations as AMS-based estimates. For a given daily or hourly duration, PDS-based quantiles were calculated for 1-, 2-, 5-, 10-, 25-, 50-, 100-, 200-, 500- and 1,000-year ARI. Selected ARIs were first converted to AEPs using the above formula and then used to calculate regional growth factors following the same regional approach and using the same L-moments that were used in the AMS analysis. The RGFs were finally rescaled by the station-specific mean annual maxima to produce the PDS quantiles for each station. Calculations were repeated for all selected durations between 1-hour and 60-day. N-minute estimates were obtained using the scaling factors calculated for AMS.

4.5.5. 90% confidence intervals on AMS and PDS frequency curves

A frequency curve that is calculated from sample data represents some average estimate of the population frequency curve, but there is a high probability that the true value actually lies above or below the sample estimate. Confidence limits determine values between which we would expect the true value to lie with certain confidence. They provide an estimate of the magnitude of uncertainty or potential error associated the precipitation frequency estimates. The interval between the confidence limits is confidence interval. The width of a confidence interval is affected by a number of factors, such as the degree of confidence, sample size, exceedance probability, distribution selection, and so on. Simulation-based procedures are typically used to estimate confidence intervals on frequency curves.

In this project, a Monte Carlo simulation procedure, as described in Hosking and Wallis (1997), was used to construct 90% confidence intervals (i.e., 5% and 95% confidence limits) on both AMS and PDS frequency curves. For each pair of daily region and daily duration (each pair of hourly region and hourly duration), 1,000 simulated datasets were generated using the same number of stations and associated record lengths as in actual regions. They were used to generate 1,000 frequency estimates at each station using the same distribution that was fitted to original data. Generated frequency estimates were sorted from the smallest to the largest and the 50^{th} value was selected as the lower confidence limit and the 950^{th} value was selected as the upper confidence limit. Confidence limits for n-minute durations were calculated using the same n-minute scaling factors that were used to estimate n-minute frequency estimates.

4.6. Spatially interpolated precipitation frequency estimates with confidence intervals

4.6.1. Derivation of mean annual maximum (index-flood) grids

As explained in Section 4.5.1, mean annual maximum values at a station serve as scaling factors to generate station-specific precipitation frequency estimates from regional growth factors (RGFs) for both AMS and PDS data. The station mean annual maximum values for selected durations were spatially interpolated to produce mean annual maximum (index-flood) grids using a hybrid statistical-geographic approach for mapping climate data named Parameter-elevation Regressions on Independent Slopes Model (PRISM) developed by Oregon State University's PRISM Group (Daly and Neilson, 1992; Daly et al., 2002). Selected durations included: 60-minute, 2-hour, 3-hour, 6-hour, 12-hour, 24-hour, 2-day, 4-day, 7-day, 10-day, 20-day, 30-day, 45-day and 60-day. The resulting high-resolution (15-seconds x 15-seconds; that is approximately 400 meters x 400 meters, or 1321 feet x 1321 feet) mean annual maximum grids then served as the basis for deriving gridded precipitation frequency estimates at different recurrence intervals using the Cascade, Residual Add-Back (CRAB) spatial interpolation procedure (described in Section 4.6.2).

Appendix A.4 provides detailed information on the PRISM-based methodology for creating mean annual maximum grids. In summary, PRISM used mean annual precipitation grids (USDA-NRCS, 1998) to estimate mean annual maximum grids. Mean annual precipitation (actually the square-root of mean annual precipitation) was used as the predictor because it is based on a large data set, accounts for spatial variation of climatic information and is consistent with methods used in previous projects, including NOAA Atlas 2 (Miller et al., 1973) and prior volumes of NOAA Atlas 14 (Bonnin et al, 2004a; Bonnin et al., 2004b; Bonnin et al. 2006). PRISM used a unique regression function for each target grid cell that accounted for: user knowledge, the distance of an observing station to the target cell, the difference between station's and target cell's mean annual precipitation, topographic facet, coastal proximity, etc. PRISM cross-validation statistics were computed where each observing station was deleted from the data set one at a time and a prediction made in its absence. Results indicated that for this project area, overall bias was less than 2 percent and the mean absolute error was less than 12 percent.

Because of the limited hourly (< 24-hour) data for this project, additional effort was made to bring the hourly station density up to that of the daily (≥ 24-hour) stations by objectively developing hourly mean annual maximum data for daily-only stations. Those data were used during the PRISM modeling of hourly durations (see Appendix A.4 for more detail).

4.6.2. Derivation of precipitation frequency estimates grids

An HDSC-developed spatial interpolation technique termed the Cascade, Residual Add-Back (CRAB) was used to convert mean annual maximum grids into grids of AMS-based and PDS-based precipitation frequency estimates for various frequencies and durations. The CRAB procedure is based on the approach used in derivation of several maps for the National Climatic Data Center's Climate Atlas of the United States (Plantico et al., 2000).

CRAB accommodates spatial smoothing and interpolating across "region" boundaries to eliminate potential discontinuities due to different RGFs as a result of the regional analysis. The CRAB process, as the term cascade implies, uses the previously derived grid to derive the next grid in a cascading fashion. The technique derives grids along the frequency dimension with quantile estimates for different durations being separately interpolated. Hence, the evolution of duration-dependent spatial patterns is independent of other durations. The CRAB process utilizes the inherently strong linear relationship between different precipitation frequencies for the same duration. This relationship is expressed as the ratio of RGFs and is a constant for all stations in the region. CRAB initially makes a generalization that all regions have the same RGF ratio between two frequencies. To account for local and regional biases, CRAB utilizes residuals defined as the differences between the precipitation frequency estimates from the generalized all-region RGF ratios and the actual precipitation frequency estimates at all stations. The residuals exhibit regional characteristics; within each individual region they are either all positive, negative or close to zero thereby supporting CRAB methodology based on residual interpolation. This, combined with the inherently strong linear predictability from one frequency to the next, makes CRAB an effective method for deriving the suite of precipitation frequency grids.

As mentioned above, the CRAB derivation process utilizes the strong linear relationship between precipitation frequency estimate at a particular duration and frequency (*predictor* variable), and the precipitation frequency estimate at next rarer frequency of the same duration. Figure 4.6.1 shows an example of the relationship for 24-hour duration between the 1-in-50 quantiles (predictor variable) and 1-in-100 quantiles for the Hawaiian Islands. The R-squared value here of 0.996 is very close to 1.0, which was common throughout all of the regressions. Since this relationship was calculated using all stations in the project area, the slope of this relationship (1.12) can be thought of as an average domain-wide RGF ratio between 1-in-100 and 1-in-50 annual exceedance probabilities for 24-hour duration. Regional differences are then accounted for by using at-site residuals.

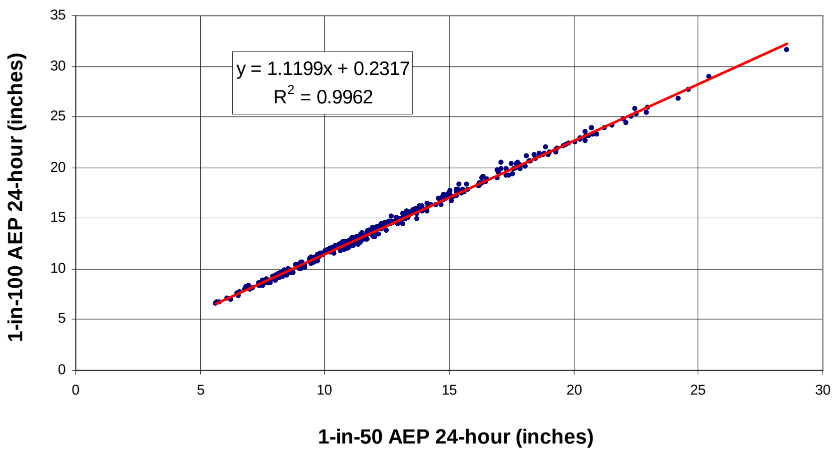


Figure 4.6.1. An example from NOAA Atlas 14 Volume 4 for 24-hour duration showing a scatter plot of 1-in-100 precipitation frequency estimates (y) versus 1-in-50 precipitation frequency estimates (x) based on annual maximum series (in inches). Linear regression line is also shown.

Derivation of precipitation frequency grids using CRAB and example results pertinent to NOAA Atlas 14 Volume 4 are summarized below in a series of steps. They are also shown in Figure 4.6.2. Since the steps are given for a fixed duration, when describing the precipitation frequency estimate, for clarity, duration is dropped and only annual exceedance probability is given. For example, precipitation frequency estimates for 24-hour duration and annual exceedance probability of 10% (1/10) is described as 1-in-10 frequency estimate.

Step 1: Development of regression equations. The cascade begins with the PRISM-derived mean annual maximum (MAM) grid for a given duration as the initial *predictor grid* and the 1-in-2 frequency estimates as the subsequent grid. As a result of spatial smoothing during PRISM interpolation, it is possible that at-site MAM values calculated directly from AMS data were slightly different from corresponding PRISM-derived grid cell MAM estimates. To account for that difference, adjustment factors are applied to the precipitation frequency estimates across all frequencies. An adjustment factor is a station-unique value that is calculated based on the ratio of the mean annual maximum PRISM grid cell value and the point mean annual maximum computed from AMS data. In NOAA Atlas 14 Volume 4, this adjustment was generally within ±5% for all stations. Adjusted precipitation frequency estimates are considered to be *actual estimates*.

A single linear relationship is developed for each duration/frequency pair for the whole project area. To develop this global relationship, an x-y data file is built. In the initial run, x-dataset contains mean annual maxima for a given duration and y-dataset includes 1-in-2 precipitation frequency estimates for the same duration from all stations in the domain. In the subsequent run, x-dataset consists of 1-in-2 precipitation frequency estimates and y-dataset consists of 1-in-5 estimates; etc. For each individual region, the slope of regression line approximates 1-in-2 RGFs in the initial run and RGF ratios in subsequent runs.

Step 2: Development of *first guess grids*. The global linear regression relationship is then applied to the *predictor grid* to establish a *first guess grid* at next higher frequency. In the initial run, the predictor grid is mean annual maximum grid; it is used to establish the first guess 1-in-2 quantile grid. The grid values are not necessarily equivalent to the *actual* estimates which are based on a unique RGF for each region.

Step 3: Development of spatially interpolated *residual grids*. To account for the regional differences, residuals (*actual* estimates minus *predicted* estimates) at each station are calculated. Here, *predicted* estimates are those derived in the *first guess grid* (e.g., 1-in-2 estimates in the initial run). The residuals are normalized by the mean annual maximum to facilitate the interpolation of residuals to ungauged locations.

The normalized residuals at each station are then spatially interpolated to a grid using a modified version of the Geographic Resources Analysis Support System or GRASS (Neteler and Mitasova, 2002) inverse-distance-weighting (IDW) algorithm to produce a *normalized residual grid*. The IDW method used in CRAB estimates the value at an unsampled point from 12 closest points. Weights are inversely proportional to the power of the distance in meters. The IDW is done in a geographic (i.e., latitude-longitude) projection, yet distances were computed based on a basic spheroid to reflect true distances. The IDW interpolation method was selected because by definition it is an exact interpolator and therefore remains faithful to the *normalized residuals* at stations; this is important so that when the *normalized residuals* are converted back to *actual residuals* they are equal to the original residuals. Also, *normalized residuals* are highly correlated (see embedded map of normalized residuals in Figure 4.6.2) so a distance-weighting type of interpolation method is appropriate.

The *normalized residual grid* is multiplied by the original spatially interpolated mean annual maximum grid to obtain a spatially interpolated grid of *actual residuals* for the entire project area.

Step 4: Development of *pre-final grids*. The spatially interpolated grid of *actual residuals* is added to the *first guess grid* to create a spatially interpolated *pre-final* grid. To prevent error propagation potentially introduced in the internal consistency adjustment steps (described in Step 5), the *pre-final grid* is archived before being smoothed. This becomes the *predictor grid* for the next precipitation frequency grid derivation. For example, the *pre-final* (i.e., not *final*) 1-in-2 grid is used as the predictor for the 1-in-5 grid to remain faithful to the data and allow patterns to develop without any differences that may be introduced by adjustments and filters.

To promote smooth contours and remove unnatural variability in the spatially distributed precipitation frequency estimates the *pre-final grid* is smoothed using a small (3x3 grid cell) center-weighted block filter, thus creating the *smoothed pre-final grid*.

Step 5: Internal consistency check. To ensure internal consistency in the *smoothed pre-final* grid cell values, duration-based and frequency-based internal consistency checks are conducted. For NOAA Atlas 14, frequency-based internal consistency violations (e.g., 1-in-100 estimate < 1-in-50 estimate) were rare and when they existed, they were minor violations relative to the precipitation frequency estimates involved. Duration-based internal consistency violations (e.g., 24-hour < 12-

hour) were more common, particularly between 120-minute and 3-hour, but again adjustments were small relative to the magnitude of precipitation frequency estimates. To mitigate internal consistency violations, the longer duration or rarer frequency grid cell value is adjusted by multiplying the shorter duration or lower frequency grid cell value by 1.01 to provide a 1% difference between the grid cells. One percent was chosen over a fixed factor to allow the difference to change according to the grid cell magnitudes while at the same time providing a minimal, but sufficient, adjustment without changing otherwise compliant data in the process. The duration-based check and adjustment is conducted first, resulting in a new pre-final grid, which is then subjected to the frequency-based check and adjustment. The resulting grid becomes the *final grid* for the particular frequency and duration.

Development of hourly grids. The limited hourly (<24-hour) duration dataset was not sufficient to accurately resolve patterns at the final high spatial resolution (15-seconds), therefore so called hourly "pseudo data" were generated at all daily-only stations to create a more coherent spatial pattern in the hourly durations. This increased the hourly duration dataset by 292 stations (from 71 to 363 stations), thereby providing the station density necessary to accurately resolve important spatial patterns that would have otherwise been undetected. Adding such data reduces uncertainty in areas with no hourly data.

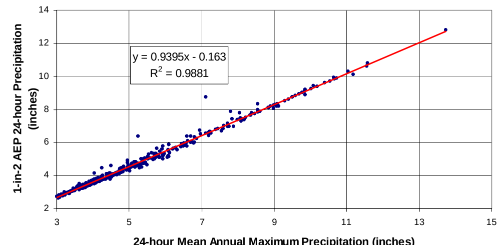
The pseudo precipitation frequency estimates were generated by applying ratios of x-hour estimates to 24-hour estimates that were spatially interpolated using IDW algorithm, based on co-located daily and hourly stations. The ratio at each co-located station was calculated using the hourly station's 24-hour precipitation frequency estimate to its x-hour precipitation frequency estimate. The interpolated ratio was then applied to the daily-only 24-hour precipitation frequency estimates to generate the pseudo hourly data at that station location. The mitigation provided a smoother, more meteorologically-sound transition from hourly to daily precipitation frequency estimates.

Development of n-minute grids. Because of the small number of n-minute data available for the Hawaiian Islands, durations shorter than 60-minute (i.e., n-minute precipitation frequency estimates) were calculated by applying n-minute scaling factors to *final grids* of spatially interpolated 60-minute precipitation frequency estimates. The scaling factors were developed using ratios of n-minute quantiles to 60-minute quantiles from co-located n-minute and hourly stations (see Table 4.5.1 and discussion in Section 4.5.3) and were applied for all annual exceedance probabilities. The appropriate 60-minute grids were multiplied by the scaling factors to create the *final* n-minute precipitation frequency grids. These scaling factor grids were also used for both the n-minute upper- and lower-confidence limit grids.

Duration x fixed. Start with PRISM mean annual maximum grid for duration x (see Section 4.6.1 for details).

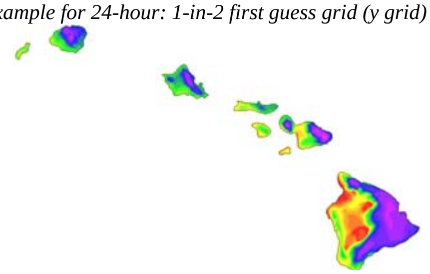
Build an x-y data file using data from all stations in the domain. Calculate slope and y-intercept of a linear regression line.
For AMS initial run: x - mean annual maximum;
y - precipitation quantile (or lower/upper confidence limit) for 1-in-2 AEP;
Subsequent run: x - quantile (confidence limit) estimate for 1-in-2 AEP;
y - quantile estimate for 1-in-5 AEP, etc.

Example for 24-hour: mean annual maxima (x) vs. 1-in-2 AMS-based frequency estimates (y)



Calculate a **first guess y grid** using above regression equation. Initially, PRISM mean annual maximum grid values are used as predictors.

Example for 24-hour: 1-in-2 first guess grid (y grid)



Calculate residuals (actual minus predicted y values). Normalize residuals by dividing by mean annual maxima, regardless of iteration.

Spatially interpolate and smooth the **normalized residual** values using inverse-distance weighting.

Example for 24-hour: 1-in-2 normalized residual grid

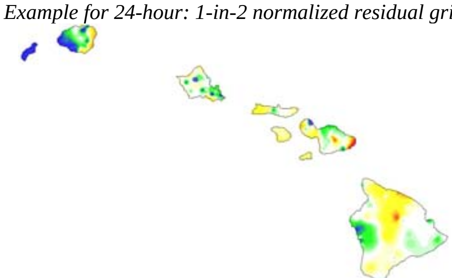
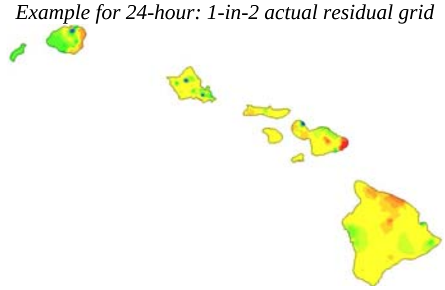


Figure continues on next page.

ITERATION: Repeat for each frequency

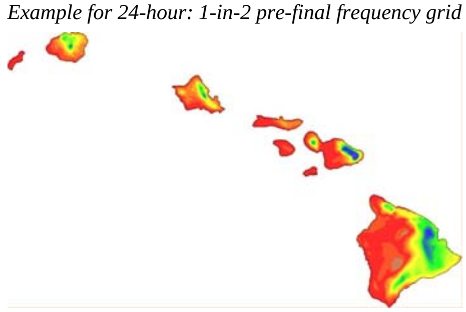
Multiply the **normalized residual grid** by the mean annual maximum grid, regardless of iteration, to obtain a grid of **actual residuals**.

Example for 24-hour: 1-in-2 actual residual grid



Add the actual residual grid to the first guess grid to obtain **pre-final grid**.

Example for 24-hour: 1-in-2 pre-final frequency grid



Save pre-final grid and use it in iteration as the next **predictor grid**.

Apply filter to the pre-final grid to promote smooth contours.

Check the **pre-final smoothed grid** for duration-based inconsistencies. For grid cells with inconsistencies, replace current values with values that are 1% higher than corresponding values calculated for previous duration.

Check the **pre-final, smoothed grid** for frequency-based inconsistencies. For grid cells with inconsistencies, replace current values with values that are 1% higher than corresponding values calculated for previous frequency. The result is the **final grid**.

If x & y represent upper and/or lower precipitation frequency bounds, apply additional consistency checks (e.g., make sure that upper confidence limits are higher than corresponding quantiles).

If duration equals 60-minutes, calculate the n-minute (5-, 10-, 15- and 30-min) grids by applying the domain-wide 60-min to n-min scaling factors to the final grid.

Figure 4.6.2. Flowchart of the cascade residual add-back (CRAB) grid derivation procedure.

Validation. Jack-knife cross-validation technique was used to evaluate CRAB performance for interpolating precipitation frequency estimates. The jackknife cross-validation exercise entailed running the CRAB procedure with a station in the dataset, storing the target grid cell value (at the station), then running CRAB without the station and comparing the target grid cell values. A perfect validation would result in equal precipitation frequency values with and without the station (i.e., 0% difference). It was cost prohibitive to re-create the PRISM mean annual maximum grids for each cross-validation iteration. For this reason, the cross-validation results reflect the accuracy of the CRAB procedure based on the same mean annual maximum grids. The validation was done on 60-minute precipitation frequency estimates for 1-in-100 AEP. A histogram in Figure 4.6.3 shows the distribution of differences in 1-in-100 AEP 60-minute frequency values with and without the station. For approximately 75% of stations in the project area, differences were less than ±5%. The largest differences were up ±15%, but they occurred in less than 7% of all stations. Based on the results shown in the figure, overall CRAB did a good job in reproducing the values in the absence of station data. There is a tendency for CRAB to slightly under-predict the precipitation frequency values.

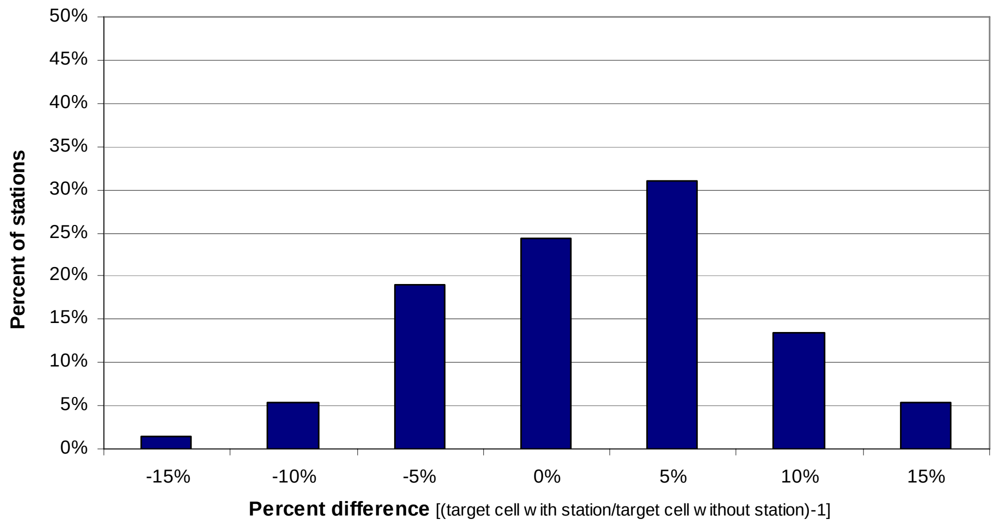


Figure 4.6.3. 100-year 60-minute jackknife cross-validation results.

Derivation of upper/lower limit confidence intervals grids. The upper and lower limit precipitation frequency grids were also derived using the CRAB procedure. Although the upper (lower) limit precipitation frequency estimates were slightly less stable than the mean grids, they still exhibited strong linear relationships with the previous (*predictor*) grid. The PRISM-produced mean annual maximum grid for a given duration was used as the initial *predictor grid* for the 1-in-2 AEP upper and lower limit precipitation frequency estimate grids. Figure 4.6.4 shows an example of the relationship between mean annual maxima and 1-in-2 upper limit as a scatter plot for 24-hours.

Similar to the precipitation quantile grids, the upper and lower limit grids were evaluated and adjusted for internal consistency. Although very rare, duration-based adjustments were made to ensure the upper (lower) limit grid cell values were larger (smaller) than the mean values. In cases where upper limit (lower limit) was lower (higher) than its corresponding precipitation frequency estimate, the upper (lower) limit grid was adjusted up (down) by 1% of the mean grid. Like the precipitation quantile grids, frequency-based or duration-based adjustments were made when needed.

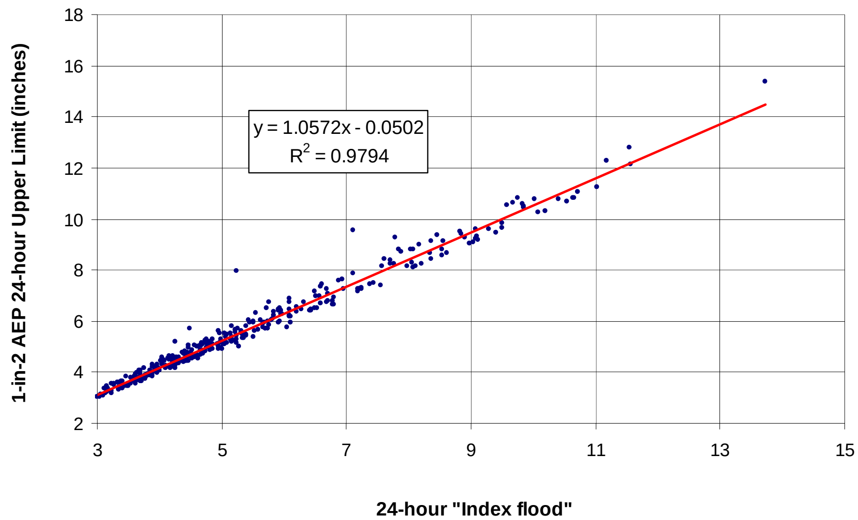


Figure 4.6.4. An example from NOAA Atlas 14 Volume 4 for 24-hour duration showing a scatter plot of upper confidence limits for 1-in-2 AEP frequency estimates (y) and the mean annual maximum estimates (x).

4.6.3. Derivation of isohyetals of precipitation frequency estimates

Isohyetal (contour) files were created from the grids of PDS-based precipitation frequency estimates for use with geographical information systems (GISs). The isohyetals are provided as Environmental Systems Research Institute, Inc. (ESRI) line shapefiles. The isohyetals were created by contouring the grid files with GRASS's *r.contour* command and were then exported as shapefiles with *v.out.shapefile* command. In order to keep the isohyets and grids consistent, no line generalization or smoothing was conducted. The precision, resolution, and smoothness of the grids were sufficiently high to result in smooth contour lines.

The choice of contour intervals was determined by an algorithm which used the maximum, minimum, and range of grid cell values. The number of individual contour intervals was constrained between 10 and 30; however, some of the n-minute grids did not exhibit the range necessary to meet the 10 interval threshold and therefore have fewer than 10 contour intervals. All of the intervals are evenly divisible by 0.10 inches – the finest interval. A script that computed the appropriate contour intervals and shapefiles also generated Federal Geographic Data Committee compliant metadata for the shapefiles and a "fact" file; the HTML-formatted fact file provides details of the shapefile and also includes a list of the contour intervals. To simplify the downloading of the isohyetal shapefiles from the Precipitation Frequency Data Server (PFDS), all of the shapefile components (*.shp, *.dbf, and *.shx, *.prj), metadata and fact file were compiled and compressed into a single archive file containing many files (*.tar). For projection, resolution and other details of the shapefiles, please refer to the metadata and/or fact file.

The isohyetal shapefiles were created to serve as visual aids and are not recommended for interpolating final point or area precipitation frequency estimates for design criteria. Users are urged to take advantage of the grids or the Precipitation Frequency Data Server user interface for accessing final estimates (see Section 5).

4.6.4. Creation of cartographic maps

The isohyetal shapefiles were used to create color cartographic maps of PDS-based precipitation frequency grids. The maps were created using Environmental Systems Research Institute, ArcGIS 9.1 software, in particular ArcMap (ESRI, 2003). Although in appearance the cartographic maps look to be comprised of polygons, enclosed two-dimensional cells, they are not. Instead, color shading of the grids combined with the line shapefiles provides the clean look of polygons. The cartographic maps are provided in an Adobe Portable Document (PDF) format for easy viewing and printing. The scale of the maps is 1:1,250,000 when printed in their native size, 17” x 22” (ANSI C), however the maps can be printed at any size. Users should be mindful that future maps and/or other projects may be in different scales or print sizes.

The color cartographic maps were created to serve as visual aids and, unlike Technical Papers No. 43 and No. 51, are not recommended for interpolating point or area precipitation frequency estimates for design criteria. Users are urged to take advantage of the Precipitation Frequency Data Server graphical user interface for accessing estimates (see Section 5).

5. Precipitation Frequency Data Server (PFDS)

5.1. Introduction

NWS precipitation frequency estimates have traditionally been delivered in the form of Weather Bureau Technical Papers and Memoranda as well as NOAA Atlases. These are hard copy (i.e., paper) documents.

NOAA Atlas 14 precipitation frequency estimates are now delivered entirely in digital form in order to make the estimates more widely available and to provide them in various formats. The Precipitation Frequency Data Server (http://hdsc.nws.noaa.gov/hdsc/pfds/) is a point-and-click interface developed as the primary web portal for precipitation frequency estimates and associated information (Durrans and Brown, 2002; Parzybok and Yekta, 2003).

5.2. Underlying data

The PFDS operates from a set of ASCII grids of precipitation frequency estimates and lower and upper bounds of the 90% confidence interval. Table 5.2.1 shows the complete table of average recurrence intervals (1-year to 1,000-year) and durations (5-minutes to 60-days) for which estimates are available from the PFDS for any particular location.

Table 5.2.1. Average recurrence intervals (ARI) and durations for which precipitation frequency estimates as well as 90% confidence intervals are available from the PFDS.

Duration	ARI									
	1-yr	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	200-yr	500-yr	1,000-yr
5-minute	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
10-minute	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
15-minute	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
30-minute	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
60-minute	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
120-minute	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3-hour	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
6-hour	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
12-hour	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
24-hour	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
48-hour	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
4-day	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
7-day	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
10-day	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
20-day	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
30-day	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
45-day	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
60-day	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

The PFDS operates directly from ArcInfo (ESRI, 2003) ASCII Grids. The same grids can be downloaded from the website and imported into a Geographical Information System (GIS). The ASCII grids, which represent the official estimates, have the following pertinent metadata:

- Resolution: 15-seconds (about 400 meters x 400 meters or 1321 feet x 1321 feet);
- Units: inches*1000 (integer);
- Projection: geographic (longitude/latitude);
- Datum: WGS 1972;
- No data value: -9999.

The PFDS operates with conventional web-tools, including cgi-bin (Perl) scripts, JAVAScript and a C program. The main cgi-bin script is activated when a user selects a location, either by manually entering a longitude/latitude coordinates, selecting a station, or clicking a location on the state map. The cgi-bin script develops a comprehensive output web page on the fly.

5.3. Methods

Since the PFDS is not an Internet Map Server, a so-called "information" function had to be coded so that when provided a longitude/latitude coordinate, the PFDS could return the appropriate precipitation frequency and confidence limit estimates. "Getcell," a C-compiled program, was written to accomplish this function. "Getcell" uses the header information provided in the ArcInfo ASCII Grid and the supplied longitude-latitude coordinate to calculate the x and y location of the desired grid cell within the grid matrix. Using the PFDS, a location can be selected by:

- Clicking on the map;
- Manually entering a longitude/latitude coordinate;
- Selecting a station from a pull-down list.

5.4. Output

After the web server has extracted all precipitation frequency and confidence limit estimates from the underlying grids, an output web page is built and displayed on-the-fly based on the users selections. There are two basic types of output: depth-duration-frequency (DDF) and the intensity-duration-frequency (IDF) graphs based on either AMS or PDS data. The PFDS provides DDF graphs in two different formats (see examples shown in Figure 5.4.1 and 5.4.2). An example of the classic IDF graph, which is widely used in engineering applications, is shown in Figure 5.4.3.

Precipitation quantiles from this Atlas are **estimates for a point location**, and are not directly applicable for an area. The **conversion of point to areal estimates** is typically done by applying an areal reduction factor to the point estimates. If areal estimate is needed, it can be computed using precipitation frequency estimates from this Atlas by obtaining an average of the point estimates within the subject area and then multiplying that average by the appropriate areal reduction factor. Areal reduction factors have been published, for example, in the following publications: NOAA Technical Report NWS 24 (Meyers and Zehr, 1980), NOAA Technical Memorandum NWS HYDRO-40 (Zehr and Meyers, 1984), and NOAA Atlas 2 (Miller et al., 1973).

The output page also consists of data tables of the precipitation frequency depths (or intensities) and tables of the lower and upper bounds of the 90% confidence limits. These can also be downloaded as text via a button on the output page. The links provided in a header of the precipitation frequency table display precipitation magnitude-frequency curves with 90% confidence intervals for the selected duration (Figure 5.4.4). In addition, location maps and helpful links are provided. Embedded maps on the output page are provided by a hyperlink to the U.S. Census Bureau Mapping and Cartographic Resources Tiger Map Server (http://tiger.census.gov/cgi-bin/mapbrowse-tbl). The graphs (portable network graphics or ".png" format) are produced using gnuplot (http://www.gnuplot.info), while the remainder of the page is basic HTML.

Additionally, seasonal exceedance graphs are provided via a button on the top of the output page. Exceedance graphs indicate the percentage of events exceeding the corresponding annual exceedance probability for the specified duration (Appendix A.2). The purpose of the graphs is to portray the monthly seasonality of extreme precipitation events. See Figure 5.4.5 for an example. The percentages are based on regional statistics and the seasonal graphs are unique for each region. The number of stations and cumulative years of record are provided in the graph title to provide the user a sense of the amount of data used and therefore the reliability of the results. Durations include: 60-minute, 24-hour, 48-hour, and 10-day.

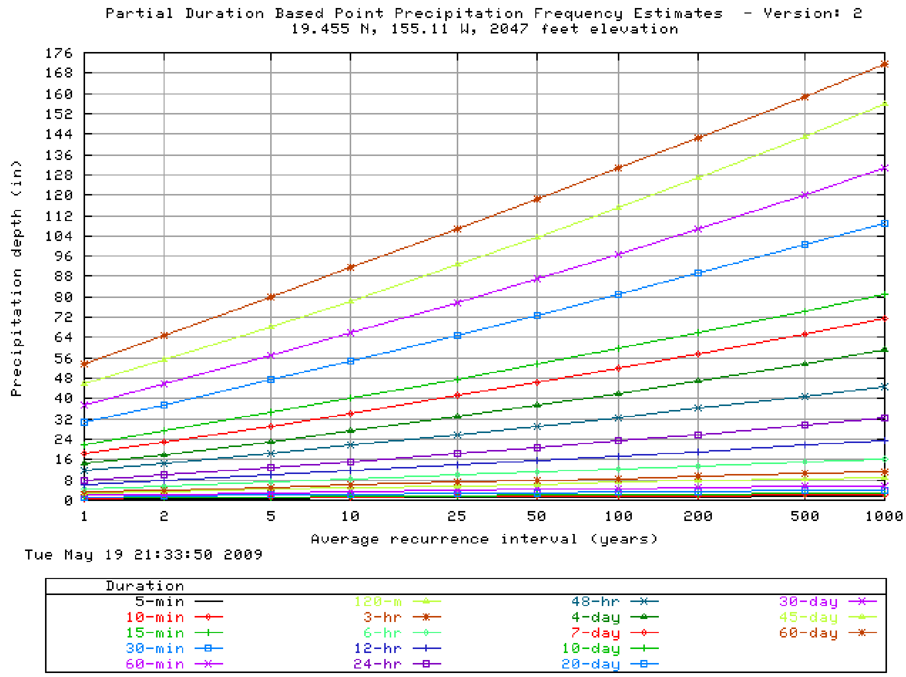


Figure 5.4.1. Sample depth-duration frequency plot with average recurrence interval on the x-axis.

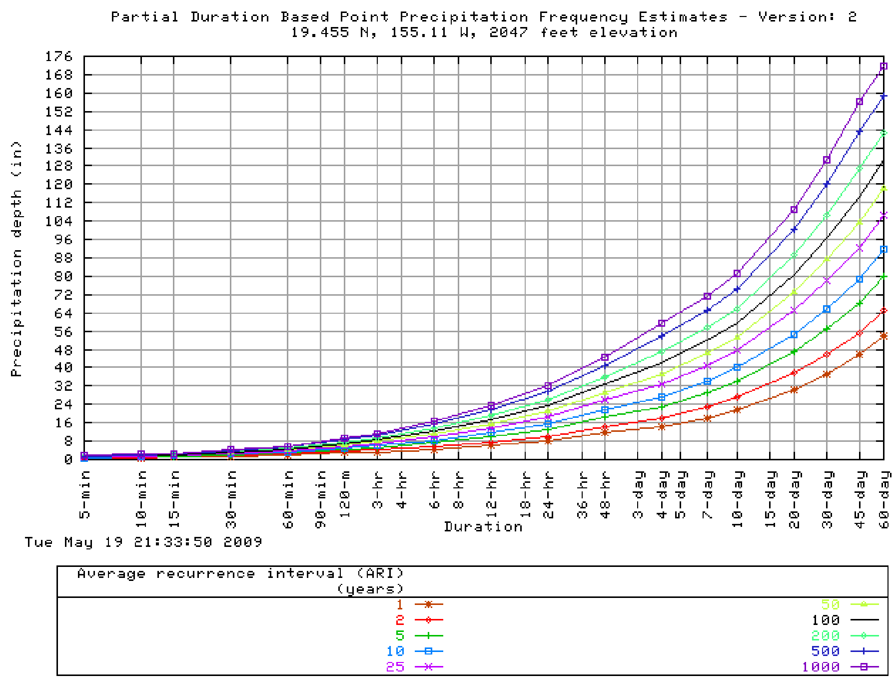


Figure 5.4.2. Sample depth-duration frequency plot with duration on the x-axis.

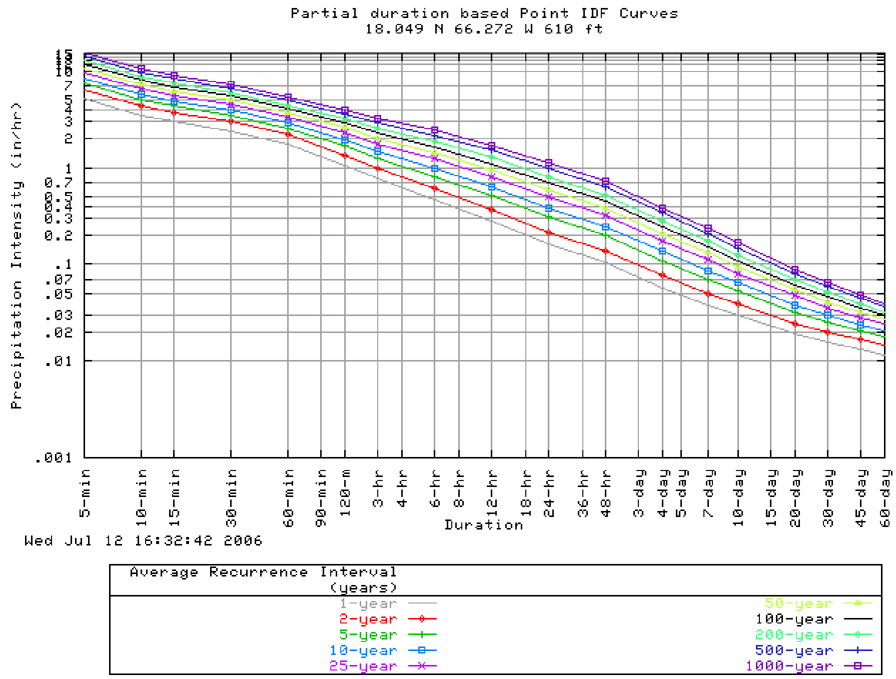


Figure 5.4.3. Sample intensity-duration-frequency (IDF) graph.

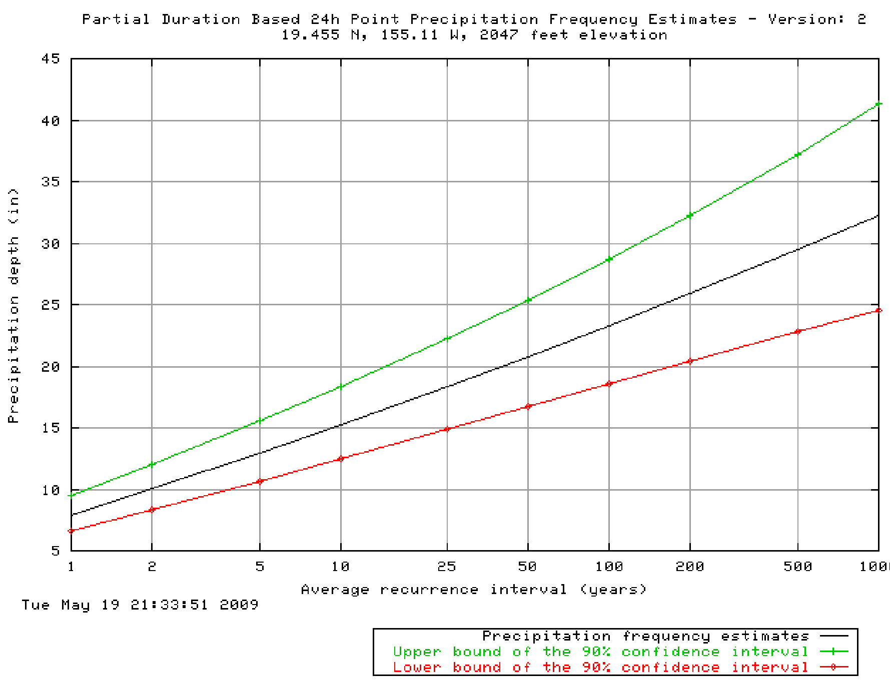


Figure 5.4.4. Sample plot of precipitation frequency estimates with the upper and lower bounds of the 90% confidence interval for24-hour duration.

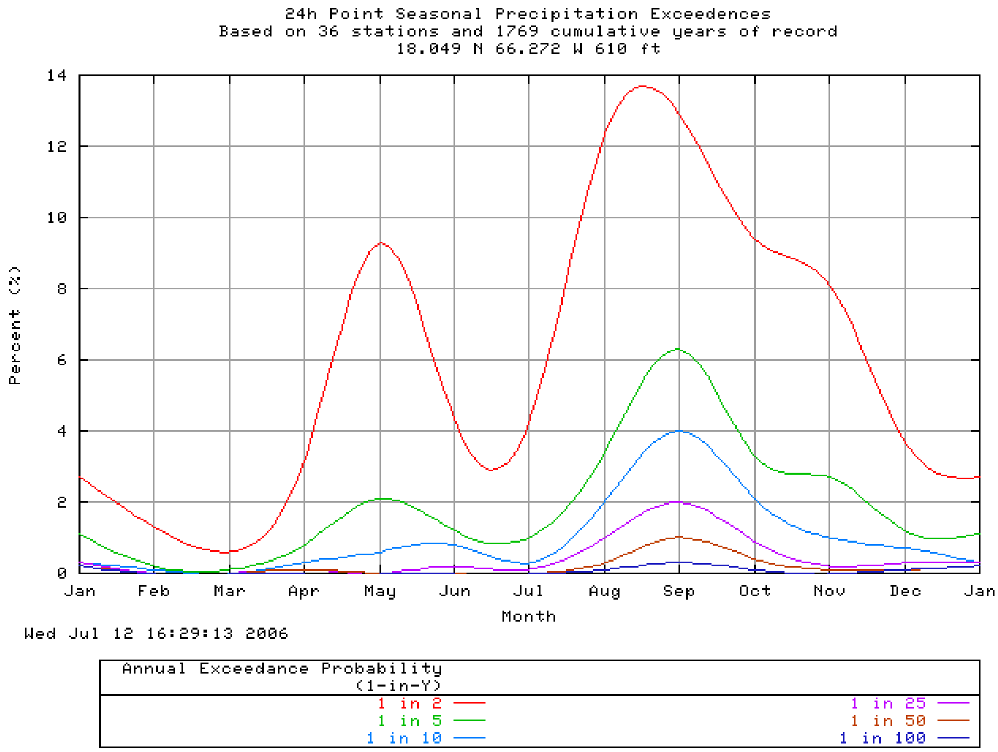


Figure 5.4.5. Sample 24-hour seasonal exceedance graph.

5.5. Using the Precipitation Frequency Data Server

The PFDS homepage (http://hdsc.nws.noaa.gov/hdsc/pfds/) has a clickable map of the United States. States with available precipitation frequency updates are indicated in blue. Upon clicking on a state, a state-specific web page appears. From this page the user selects the desired location, units, and output via a web form. The PFDS is also the portal for all NOAA Atlas 14 data formats, including:

- **Annual maximum series (AMS) dataset**
  The annual maximum series dataset used in the preparation of NOAA Atlas 14 Volume 4 are available at http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_series.html. Information regarding extraction and quality control of AMS can be found in Sections 4.3 and 4.4.

- **GIS data**
  - Shapefiles (lines, vectors)
    These are the same files used to create the cartographic maps and are recommended for visual aids only.
  - ArcInfo ASCII grids
    These grids represent the highest resolution precipitation frequency estimates from which all other formats are derived.

- **Cartographic maps**
  Cartographic maps show contour lines (available also as shapefiles from the PFDS) created from gridded precipitation frequency estimates for selected durations and average recurrence intervals. They were created to serve as visual aids and are not recommended for interpolating precipitation frequency estimates. It is strongly recommended to retrieve point precipitation frequency values from the PFDS interface which accesses the gridded data directly. Figure 5.5.1 shows an excerpt from a cartographic map.

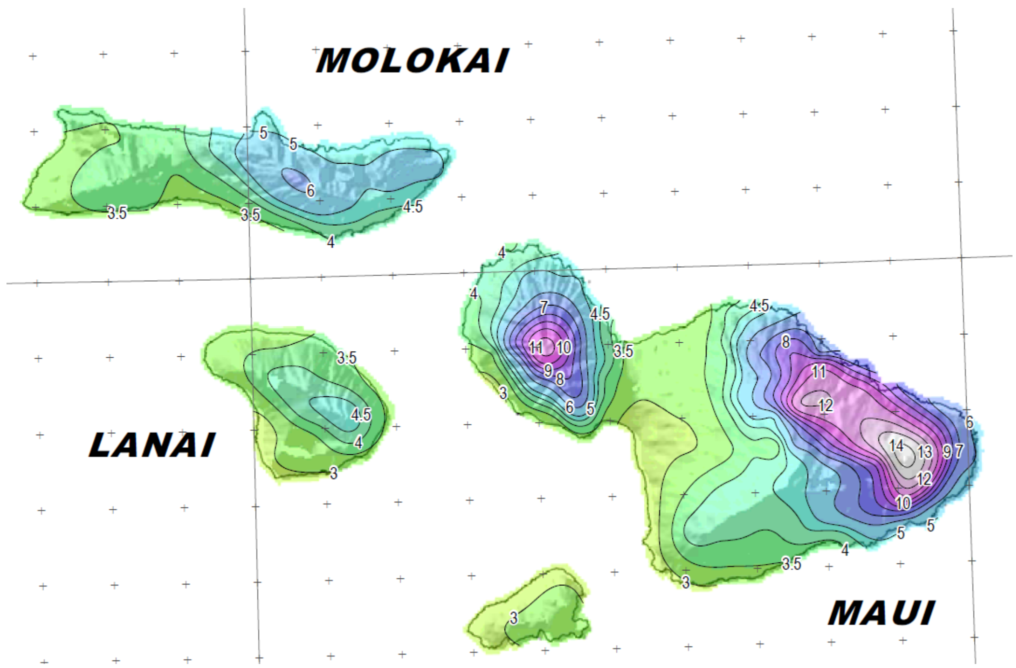


Figure 5.5.1. An excerpt of a cartographic map for 2-year ARI and 24-hour duration available from the PFDS.

- **Temporal distributions of heavy rainfall**
  Temporal distribution of heavy precipitation for use with precipitation frequency estimates in NOAA Atlas 14 Volume 4 for 1-, 6-, 12-, 24- and 96-hour durations are available from http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_temporal.html and from Appendix A.1 of this document.

- **Documentation**
  The complete NOAA Atlas 14 Volume 4 documentation is available at http://www.nws.noaa.gov/oh/hdsc/currentpf.htm#PF_documents_by_title.

It is strongly advised that users review the Federal Geographic Data Committee (FGDC) compliant metadata before using any of the GIS datasets. On-line help and frequently-asked questions (FAQ) are also available via links on the PFDS web site.

Questions regarding the use of the PFDS or its data can be addressed by emailing HDSC.Questions@noaa.gov.

6. Peer review

A peer review of the Hawaiian Islands precipitation frequency project's preliminary results was carried out during the six week period starting on September 22, 2008. 115 users, project sponsors and other interested parties were contacted via email for the review. Potential reviewers were asked to evaluate the reasonableness of point precipitation frequency estimates as well as their spatial patterns. The review included the following items:

a. at-site AMS-based depth-duration-frequency and intensity-duration-frequency curves for a range of durations for which data were available;
b. isohyethal maps of mean annual maximum (MAM) precipitation amounts for 60-minute, 12-hour, 24-hour, and 10-day durations;
c. isohyethal maps of precipitation frequency estimates for 1 in 100 annual exceedance probability and 60-minute, 12-hour, 24-hour, and 10-day durations;
d. maps showing regional groupings of stations used in frequency analysis for daily durations (≥ 24-hour) and hourly durations (< 24-hour).

The reviews provided critical feedback that HDSC used to create a better product. Reviewers' comments regarding expected spatial patterns generated further verification and/or modification of various regions and prompted development of supplemental stations in remote areas to anchor interpolation. Detailed reviewers' comments and HDSC responses can be found in Appendix A.5.

7. Comparison with Technical Papers No. 43 and No. 51

NOAA Atlas 14 Volume 4 supersedes Technical Paper No. 43, "Rainfall-Frequency Atlas of the Hawaiian Islands for Areas to 200 Square Miles, Durations to 24 Hours, and Return Periods from 1 to 100 Years" (U.S. Weather Bureau, 1962) and Technical Paper No. 51, "Two- to Ten-Day Rainfall for Return Periods of 2 to 100 Years in the Hawaiian Islands" (U.S. Weather Bureau, 1965). Technical Paper No. 43, herein after referred to simply as TP 43, published in 1962, was the most recent update of the precipitation frequencies for the Hawaiian Islands for 5-minute through 24-hour durations. Technical Paper No. 51 (TP 51), published in 1965, provided the latest update of the precipitation frequencies for the Hawaiian Islands for 2-day to 10-day durations.

Updated precipitation frequency estimates from this Atlas were examined in relation to TP 43 and TP 51 estimates for 100-year average recurrence interval. Investigation of spatial maps of relative differences (in percent) between NOAA Atlas 14 and TP 43 estimates for 1-day duration (Figure 7.1) and 1-hour duration (Figure 7.2) revealed that 100-year precipitation frequency estimates for both durations changed up to ±50%, but mostly within ±15%. Areas with significant changes in precipitation frequency have been carefully investigated. They are considered reasonable and are primarily attributed to more stations and extended data sets available for this project, and also to more robust regional frequency approaches and improved spatial interpolation techniques used in this Atlas.

The disparity in available data for NOAA Atlas 14 and TP 42 is considerable, in terms of number of stations available for frequency analysis and particularly in terms of record lengths. For example, a total of 352 daily stations (the exact number available for each duration analyzed varies due to accumulated data; see Section 4.3) with record lengths ranging from 20 to 100 years (44 data years on average) were available for this project. In contrast, only 287 daily stations with periods of record between 5 and 59 years (with possibly some years with no observations) were used in some fashion in TP 43, and of those only 159 had at least 20 years of data and so could be used directly in frequency analysis. For some stations used in both projects, 41 more years of data were available for NOAA Atlas 14. Record lengths for daily stations used in each publication are shown in Figure 7.3.

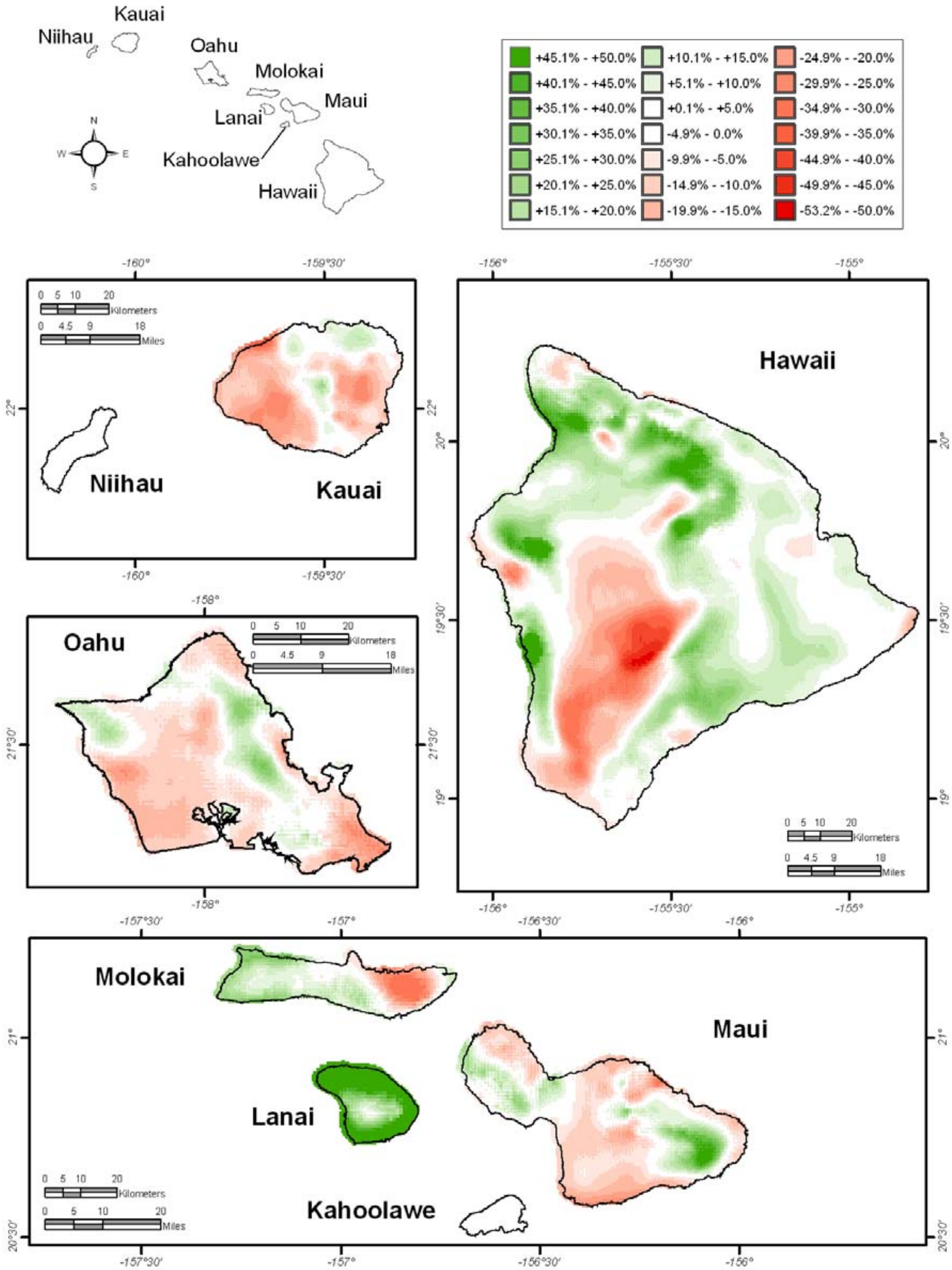


Figure 7.1. Relative differences (in percent) between NOAA Atlas 14 Volume 4 and Technical Paper 43 100-year 24-hour estimates.

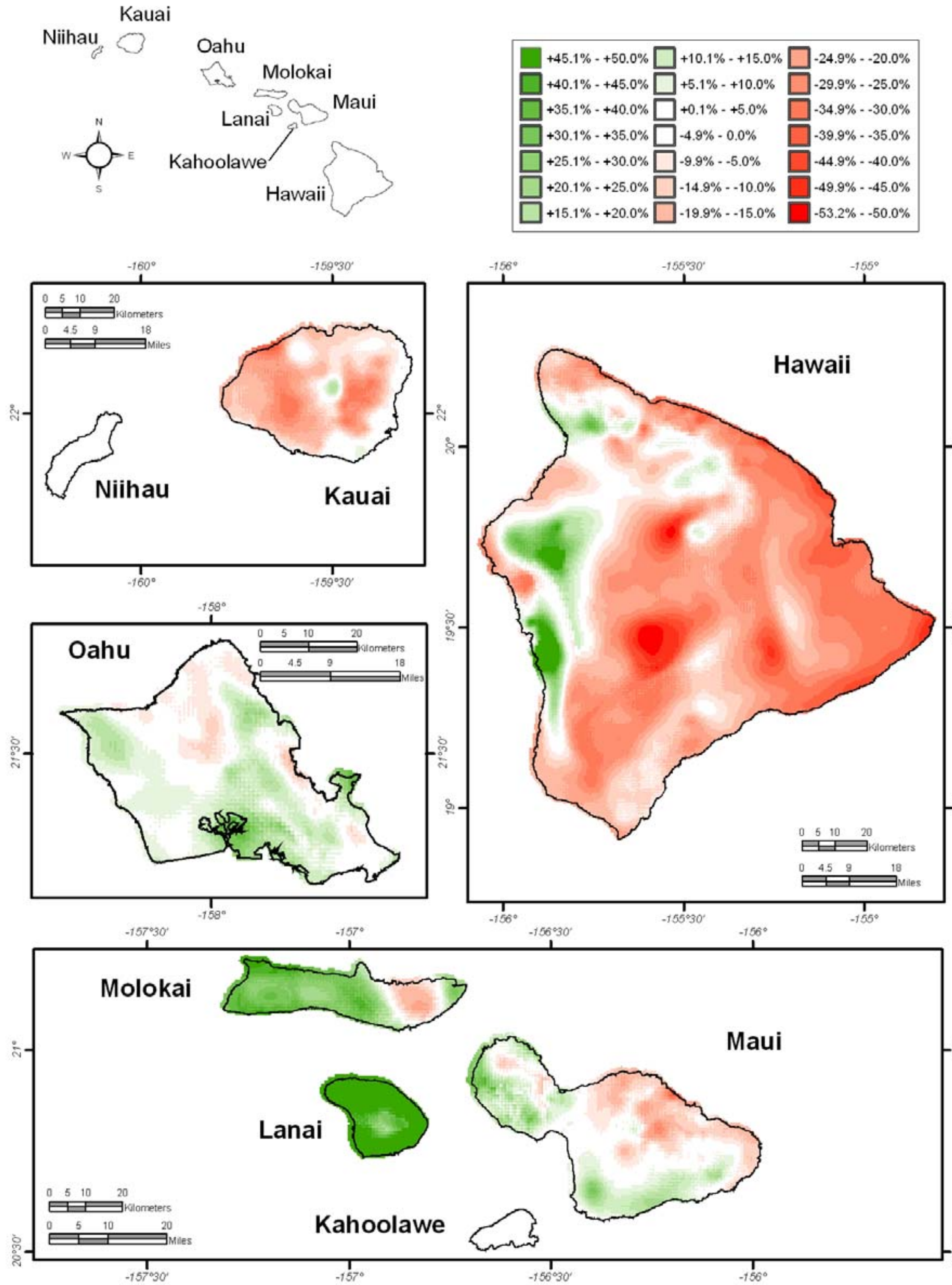


Figure 7.2. Relative differences (in percent) between NOAA Atlas 14 Volume 4 and Technical Paper 43 100-year 60-min estimates.

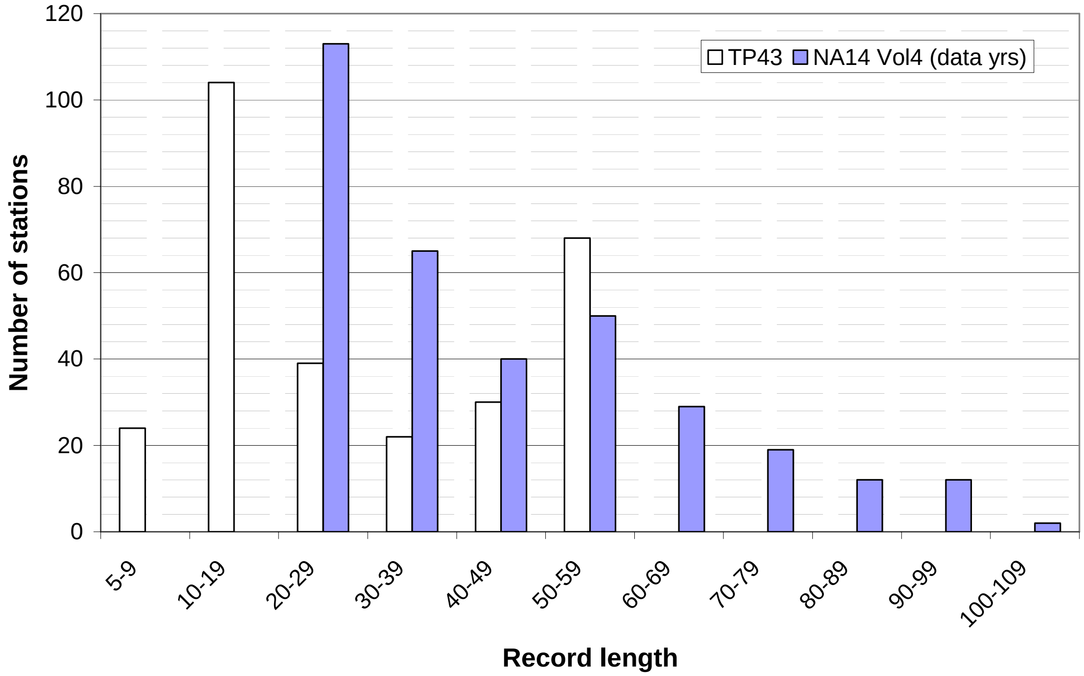


Figure 7.3. Comparison of record lengths at daily stations used in Technical Paper 43 (as years of record) and in NOAA Atlas 14 (as data years).

For longer daily durations, frequency analysis in TP 51 was done using only 52 stations with 43 years of record on average; an additional 139 stations with at least 10 years of data were used indirectly to develop relationships between 1-day and 10-day frequency estimates. In comparison, 217 to 253 daily stations (number depends on duration) were used in the NOAA Atlas 14 frequency analysis. For some stations used in both projects, 44 additional years of data were available for NOAA Atlas 14.

For hourly stations, the difference in available data between two projects is striking; 71 hourly stations were available for this project and only three hourly stations were available for TP 43, two of which had records of less than 10 years.

Evidently, the frequency analysis approach in TP 43 had to be designed to accommodate the significant percentage of stations with fairly short records; and in case of hourly durations it was based on 1-hour statistics from the continental United States. Also, isohyetal maps in TP 43 and TP 51 resulted from interpolation of frequency estimates at very few stations. This surely impacted the accuracy of the results.

Other contributors to differences in estimates are improved frequency approaches and spatial interpolation techniques used in the Atlas. In TP 43, precipitation magnitude - frequency relationships at individual stations have been computed using a single-site frequency analysis approach based on conventional moments; in NOAA Atlas 14, they were computed using an index-flood regional frequency analysis approach based on the L-moments. L-moments are generally accepted to be better suited for analysis of precipitation data that exhibit significant skewness than conventional moments; they are less subject to bias in estimation and are less susceptible to the presence of outliers in the data. The regional frequency analysis approach used in NOAA Atlas 14 has also been shown to yield more accurate estimates of extreme quantiles than the single-site frequency analysis approach used in TP 43 and TP 51.

Finally, precipitation frequency estimates are available for a wider range of durations and frequencies in NOAA Atlas 14 than in previous publications. In NOAA Atlas 14, frequency estimates are available for average recurrence intervals of up to 1,000 years and durations up to 60 days; in TP 43 and TP 51 they were available for frequencies up to 100 years and durations up to 10 days. Another important difference is that in NOAA Atlas 14, confidence intervals were constructed on AMS and PDS frequency estimates to allow for assessment of uncertainty in estimates; such information was not available from TP 43 and TP 51.

Appendix A.1 Temporal distributions of heavy precipitation

1. Introduction

Temporal distributions of heavy precipitation are provided for use with precipitation frequency estimates from NOAA Atlas 14 Volume 4 for durations of 6, 12, 24, and 96 hours covering the Hawaiian Islands. The temporal distributions are expressed in probability terms as cumulative percentages of precipitation and duration at various percentiles. The precipitation cases used to derive the temporal distributions are defined in the same fashion as those for estimating precipitation frequency for consistency. In particular, hourly annual maximum series of all stations in the project area are used.

Figure A.1.1 shows the temporal distributions of all precipitation cases for selected durations. The rainfall data were further divided into quartiles based on where in the distribution the most precipitation occurred, in order to provide detailed information on the varying distributions that were observed. Figures A.1.2 through A.1.5 depict temporal distributions for each quartile for the four durations. Digital data of the temporal distributions in a tabulate form are available for downloading at http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_temporal.html. Since the analysis was conducted using hourly rainfall data, there are six data points for 6-hour temporal distributions in the data tables, twelve data points for 12-hour temporal distributions, and so on.

2. Methodology and results

The methodology used to produce the temporal distributions is similar to the one developed by Huff (1967) except in the definition of precipitation cases. In this project, precipitation accumulation was computed for a specific time period (e.g., 6, 12, 24, and 96 hours) as opposed to a single storm event in accordance to the way a precipitation case was defined for the precipitation frequency analysis. As a result, the accumulation may contain parts of one, or more than one storm. In addition, a precipitation case was defined to start with rainfall but not necessarily end with rainfall, causing more front-loaded cases (as seen in the previous volumes) when compared with distributions derived from the single storm approach. To eliminate this bias, a constraint was imposed to exclude cases with a continuous dry period that lasted for more than 20% of the duration. This restriction produces a less biased and variant sample and better describes the temporal distributions of heavy precipitation for use with precipitation frequency estimates.

The mass curve for each precipitation case in the sample was normalized by the total precipitation and duration. That is, at each time step (converted into a percentage as the cumulative time to the case duration) rainfall accumulation was converted into a percentage of the cumulative precipitation to the total precipitation. The rainfall data were then combined and cumulative deciles of precipitation were computed at each time step. After that, the dimensionless precipitation of a given decile (e.g., 10%, 50%, or 90%) at all time steps was connected to form a curve, and the results of all nine deciles (from 10% to 90%) for a given duration were plotted in one graph as seen in Figure A.1.1 for all precipitation cases. The cases were further divided into four categories by the quartile in which the greatest percentage of the total precipitation occurred, and the procedure was repeated for each quartile to produce the graphs shown in Figures A.1.2 through A.1.5. Graphs shown in these figures are time distribution curves smoothed by various polynomial functions to improve graphical presentation. The criterion for choosing the smoothing functions was that they preserve most of the properties of the data-derived curves.

Comparing to the results in the previous NOAA Atlas 14 volumes, precipitation cases were more uniformly divided into four quartiles for each duration except for 6-hour duration. Unlike the cases of 12-, 24-, and 96-hour durations in which the number of data points can be equally divided by four, the cases of 6-hour duration contain only six data points and they cannot be evenly distributed into four quartiles. Therefore, in this analysis, for 6-hour duration, the first quartile contains rainfall cases where the most rainfall occurred in the first hour, the second quartile contains rainfall cases where the most rainfall occurred in the second and third hours, the third quartile contains rainfall cases where the most rainfall occurred in the fourth hour, and the fourth quartile contains rainfall cases where the most rainfall occurred in the fifth and sixth hours. This uneven distribution causes the difference in the number of cases contained in each quartile (see Table A.1.1). However, due to the large number of cases available for the 6-hour duration, the numbers of cases for the first and third quartiles (134 and 190) are sufficient to produce meaningful results of temporal distributions although they are a small portion of the entire sample.

Table A.1.1 provides the numbers and proportion of precipitation cases in each quartile used to derive the temporal distributions. By imposing the restriction of continuous 20% dry period, the number of cases available for temporal distribution analysis decreased with duration because long, continuous rainfall events occurred less frequently than short-duration events.

To determine whether distributions varied appreciably across the project area, temporal distributions based on data from each hourly region were computed separately, and then compared to the distributions computed for the project area as a whole. The distributions were nearly identical, although there was more noise in the distributions from the separate regions due to smaller sample size. As a result, the temporal distributions presented here are based on the entire project area because of the larger sample size and because the distributions varied little by region.

3. Interpretation

Figure A.1.1 presents cumulative probability plots of temporal distributions for the 6-, 12-, 24-, and 96-hour durations for the project area. Figures A.1.2 through A.1.5 present the same information for categories based on the quartile of most precipitation. The x-axis is the cumulative percentage of duration; and the y-axis is the cumulative percentage of precipitation.

The data on the graph represent the average of many cases illustrating the cumulative probability of occurrence at 10% increments. For example, 30% of the cases in which precipitation is concentrated in the beginning of the duration will have distributions that fall above and to the left of the 30% curve. At the other end of the spectrum, only 10% of the cases are likely to have a temporal distribution falling to the right and below the 90% curve. In the latter case, the bulk of the precipitation falls toward the end of the time period. The 50% curve represents the median temporal distribution on each graph.

First-quartile graphs consist of cases where the greatest percentage of the total precipitation fell during the first quarter of the duration (e.g., the first 3 hours of a 12-hour duration). The second, third, and fourth quartile plots are similarly for cases where the most precipitation fell in the second, third, or fourth quarter of the duration.

The temporal distributions consistently show a greater spread, and therefore greater variation, between the 10% and 90% probabilities as duration increases. Longer durations are more likely to have captured more than one event separated by drier periods; however, this has not been objectively tested as the cause of the greater variation at longer durations.

The following is an example of how to interpret the results using Figure A.1.4a and Table A.1.1. Of the 1086 cases of the 24-hour duration, 282 of them were first-quartile cases:

- In 10% of the cases, 50% of the total rainfall (y-axis) fell in the first 3.6 hours (15% on the x-axis). By the 12th hour (50% on the x-axis), 88% of the precipitation had fallen.
- A median case of this type will drop half of its total rain (50% on the y-axis) in 6.5 hours (27% on the x-axis).
- In 90% of the cases, 50% of the total precipitation fell by approximately 10.8 hours (45% on the x-axis).

4. Summary

The results presented here can be used for determining temporal distributions of heavy precipitation at particular levels of probability for durations of 6, 12, 24, and 96 hours. The results are designed for use with precipitation frequency estimates and may not be the same as the temporal distributions of single storms. The temporal distributions show a greater spread between the deciles with increasing duration as seen in Figures A.1.1 to A.1.5. In Table A.1.1, a majority of the precipitation cases are second-quartile cases for all durations, although the differences between the numbers of cases for the quartiles are small.

Care should be taken in the use of these data. The data are presented in order to show the range of possibility and that the range can be broad. The data should be used in a way to reflect users' objectives. For example, while all cases represented in the data will preserve volume, there will be a broad range of peak flow that could be computed. In instances where peak flow is a critical design criterion, users may want to consider temporal distributions likely to produce higher peaks rather than using the median (or 50%) curve. Moreover, users might consider using results from one of the quartiles rather than from the "all cases" sample to achieve more appropriate results for their studies.

Table A.1.1 Numbers and proportion of precipitation cases in each quartile for all durations.

Duration (hours)	1st quartile	2nd quartile	3rd quartile	4th quartile	Total number of cases
6	134 (7%)	980 (49%)	190 (9%)	700 (35%)	2004
12	386 (24%)	461 (29%)	436 (28%)	304 (19%)	1587
24	282 (26%)	286 (26%)	275 (25%)	243 (23%)	1086
96	178 (27%)	188 (29%)	170 (26%)	115 (18%)	651

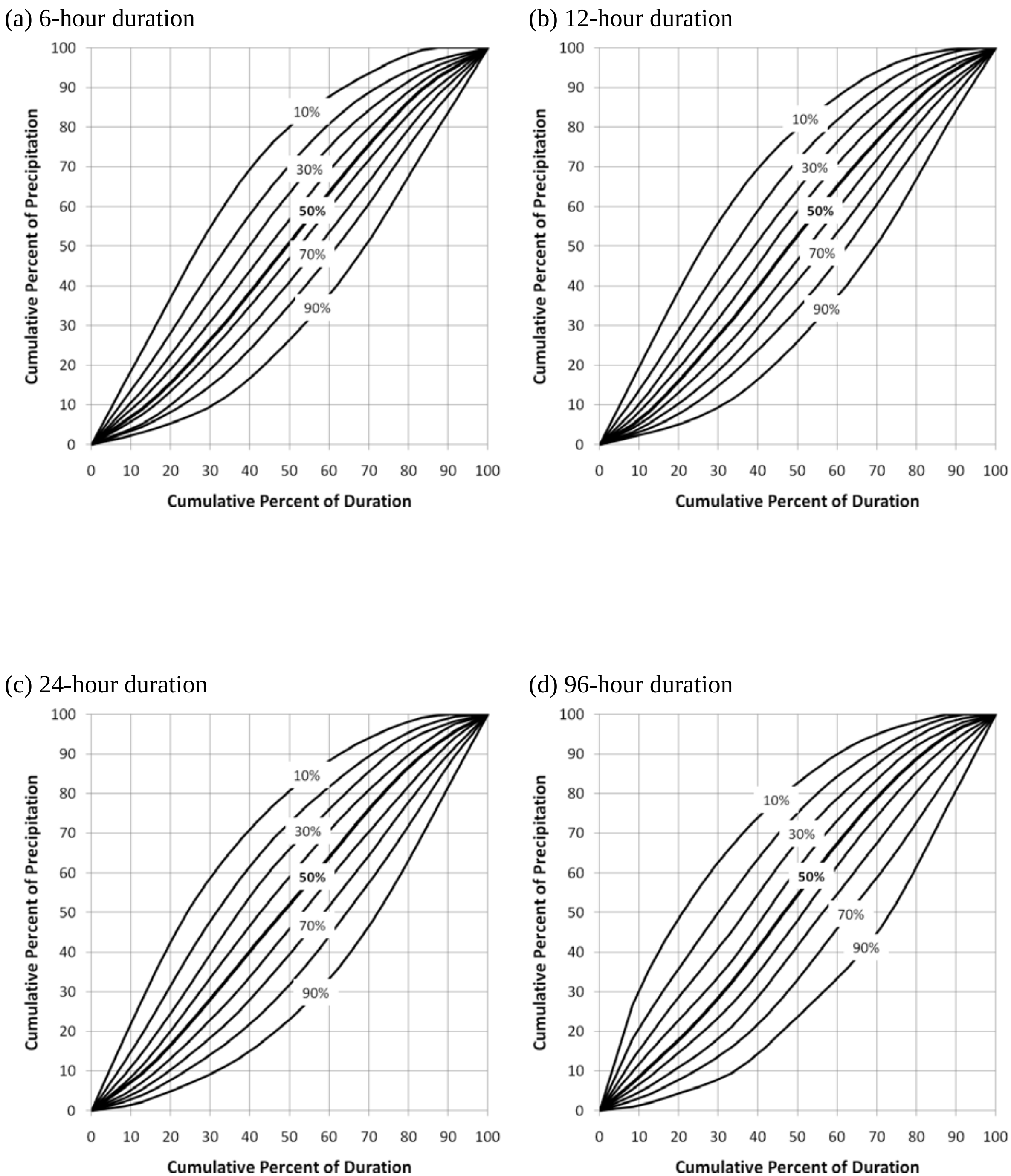
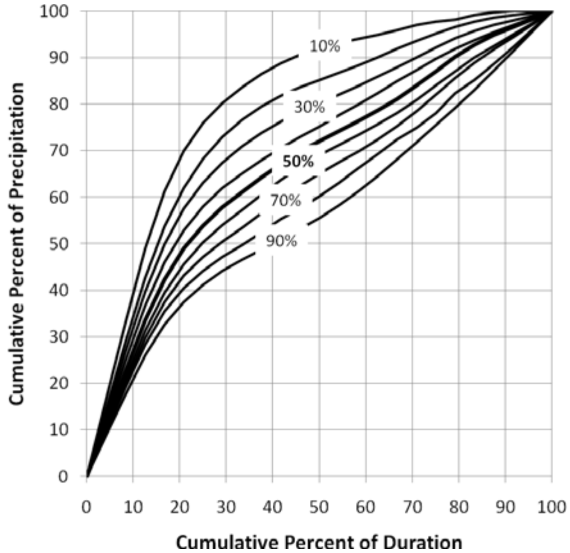
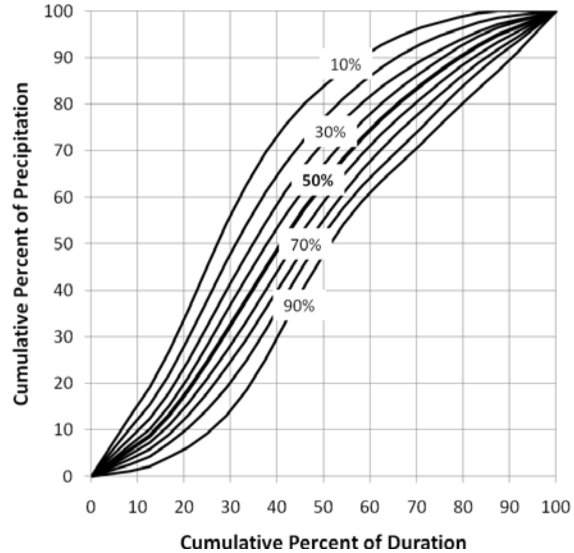


Figure A.1.1. Temporal distributions of all cases for durations of (a) 6, (b) 12, (c) 24, and (d) 96 hours.

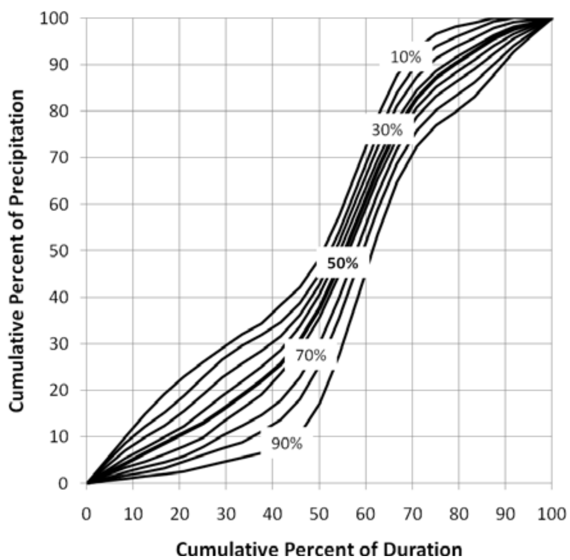
(a) First-quartile cases



(b) Second-quartile cases



(c) Third-quartile cases



(d) Fourth-quartile cases

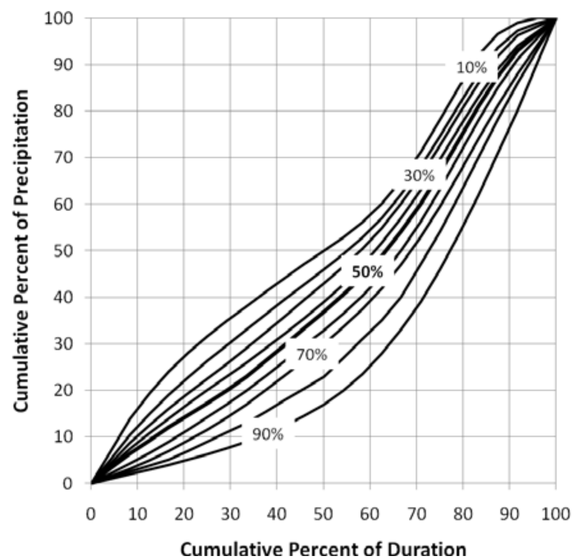
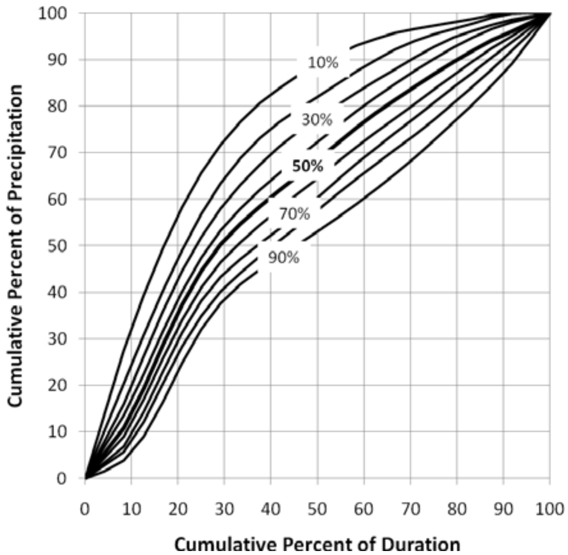
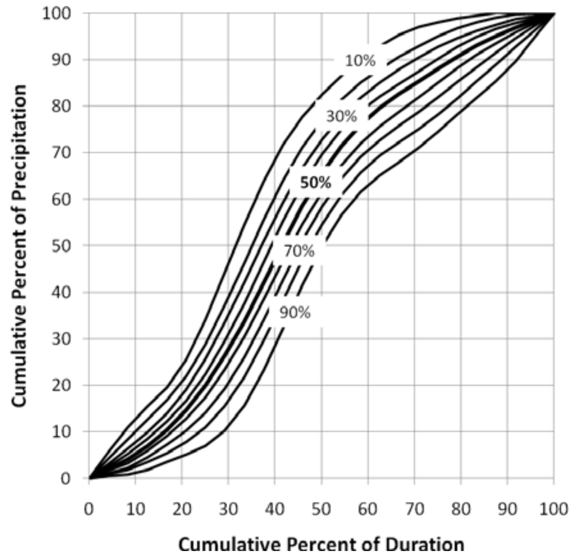


Figure A.1.2. 6-hour temporal distributions for (a) first-quartile, (b) second-quartile, (c) third-quartile, and (d) fourth-quartile cases.

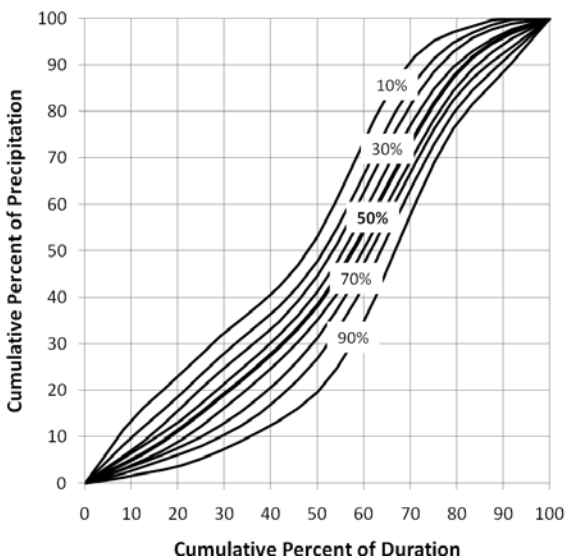
(a) First-quartile cases



(b) Second-quartile cases



(c) Third-quartile cases



(d) Fourth-quartile cases

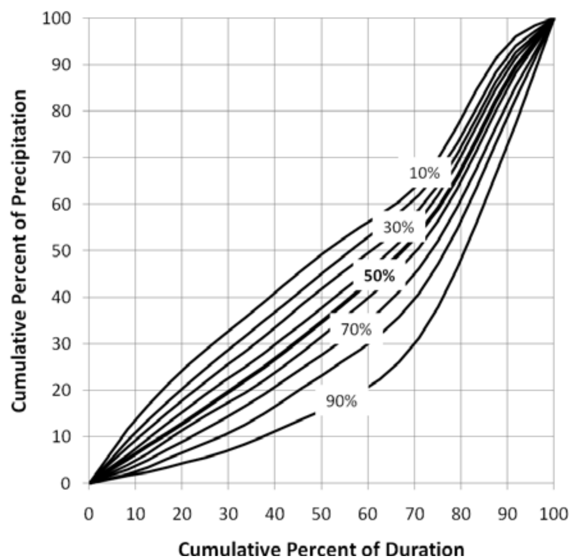


Figure A.1.3. 12-hour temporal distributions for (a) first-quartile, (b) second-quartile, (c) third-quartile, and (d) fourth-quartile cases.

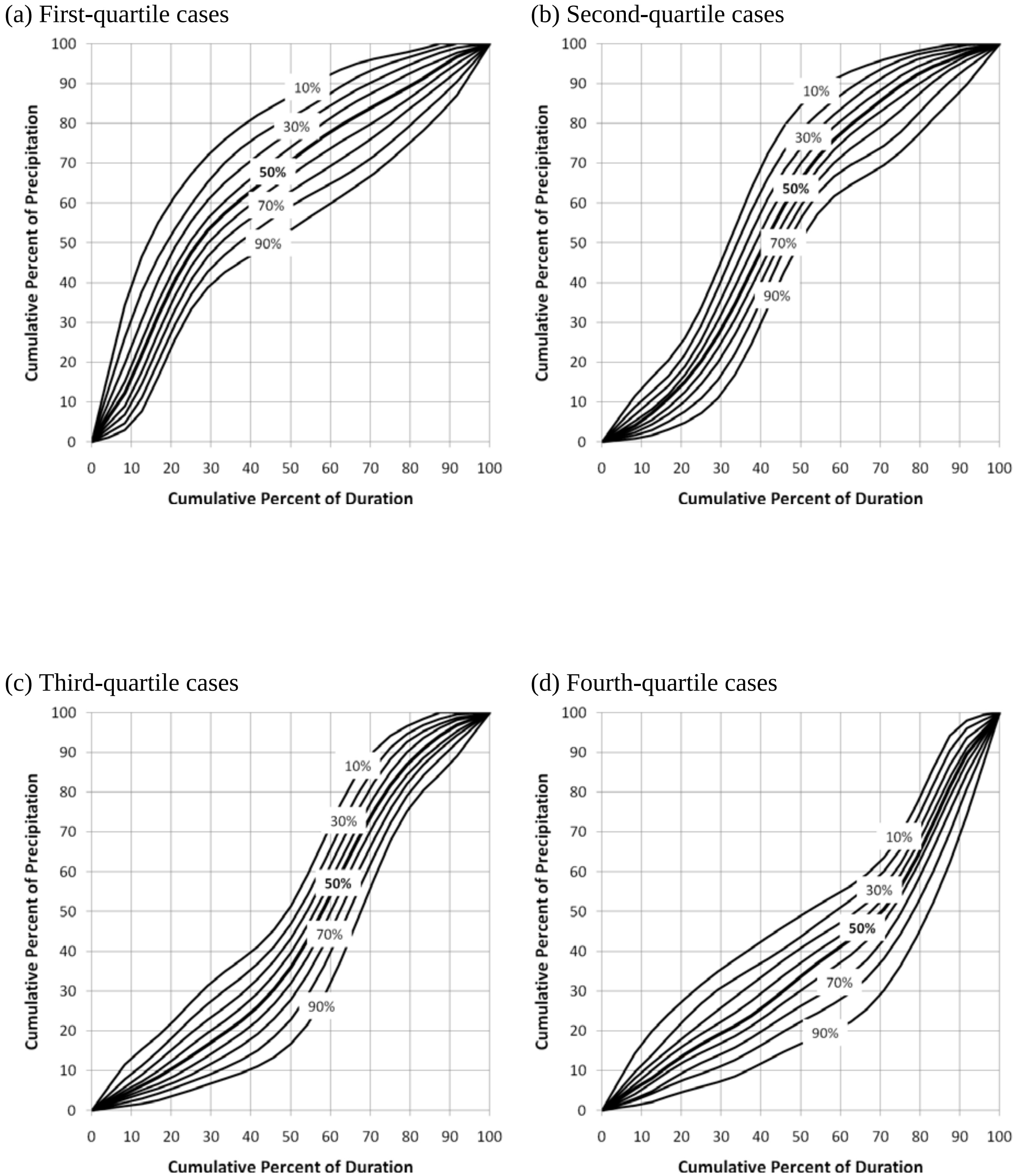
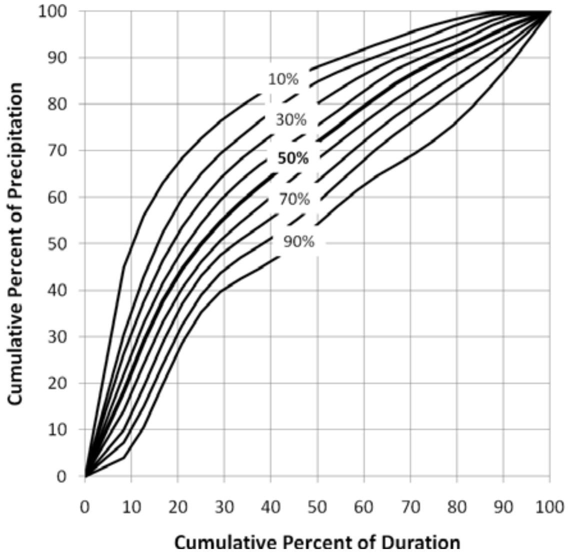
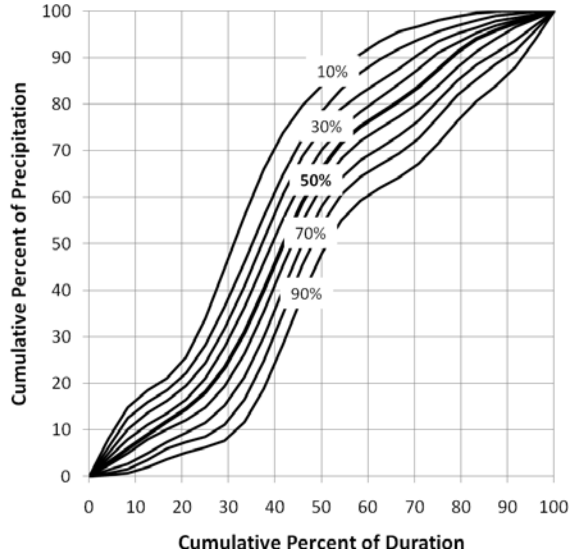


Figure A.1.4. 24-hour temporal distributions for (a) first-quartile, (b) second-quartile, (c) third-quartile, and (d) fourth-quartile cases.

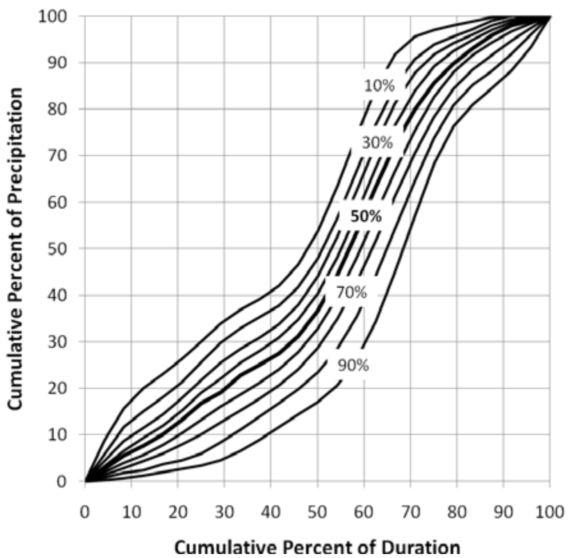
(a) First-quartile cases



(b) Second-quartile cases



(c) Third-quartile cases



(d) Fourth-quartile cases

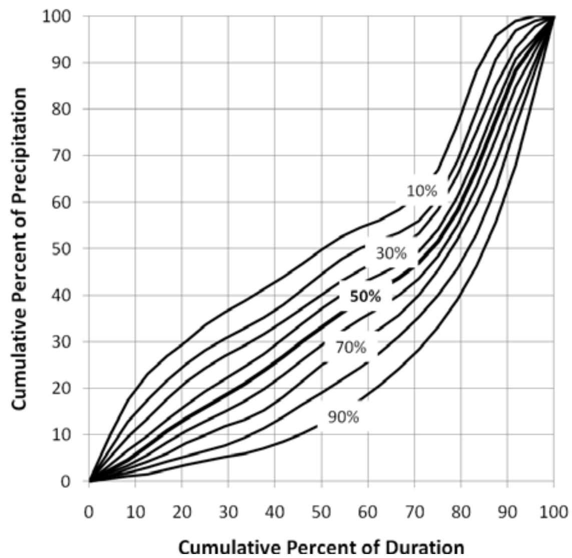


Figure A.1.5. 96-hour temporal distributions for (a) first-quartile, (b) second-quartile, (c) third-quartile, and (d) fourth-quartile cases.

Appendix A.2 Seasonality

1. Introduction

To portray the seasonality of extreme precipitation throughout the project area, precipitation amounts that exceeded the precipitation frequency estimates with selected annual exceedance probabilities (AEPs) for chosen durations were examined for each hourly or daily region. Graphs showing the monthly variation of the exceedance for a region are provided for each location in the project area via the Precipitation Frequency Data Server (PFDS) at http://hdsc.nws.noaa.gov/hdsc/pfds/. On the PFDS webpage, a user can view the seasonal exceedance graphs by clicking the "Seasonality" button when a point (or station) is selected.

2. Method

Exceedance graphs were prepared showing the percentage of events that exceeded the precipitation frequency estimate for a given duration and annual exceedance probability in each month for each region. The precipitation frequency estimates were derived from annual maximum series at each station in the region as described in Section 4.5. Each graph shows the exceedances with the 1 in 2, 5, 10, 25, 50, and 100 AEPs for a given duration. Results are provided for durations of 60 minutes, 24 hours, 2 days, and 10 days in separate graphs. The results were compiled for each hourly region (Figure 4.5.2) for the 60-minute duration and each daily region (Figure 4.5.1) for the 24-hour, 2-day, and 10-day durations.

To prepare the graphs, the number of events exceeding the precipitation frequency estimate at a station for a given AEP was tabulated for the selected duration. Events were extracted in the same manner as for the generation of the annual maximum series (Section 4.3). The output for all stations in a given region was then combined, sorted by month, normalized by the total number of data years in the region, and plotted via the PFDS.

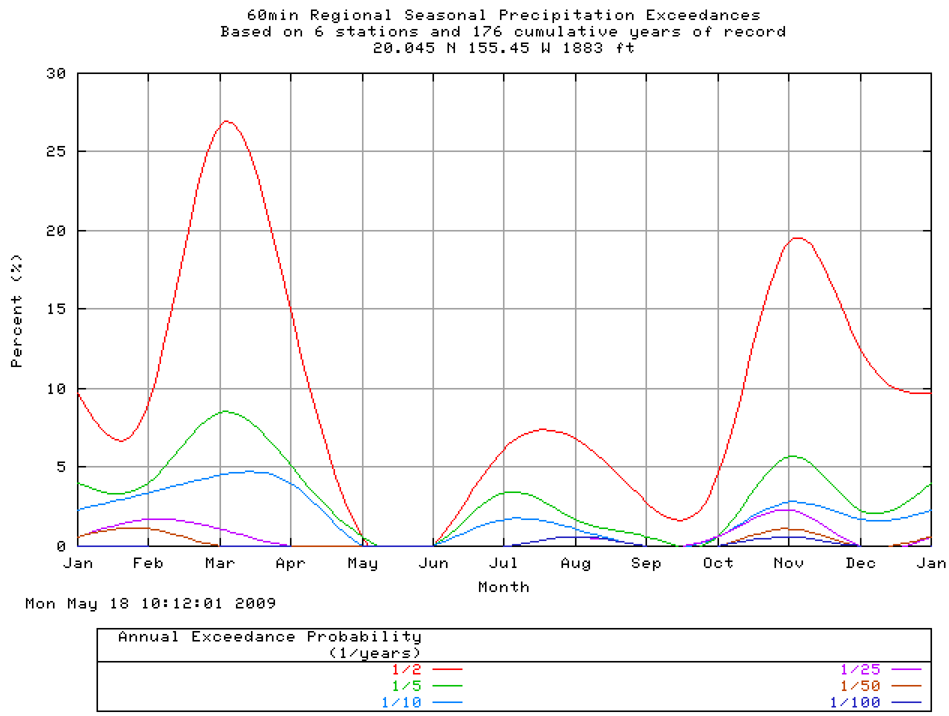
3. Results

The exceedance graphs (see Figure A.2.1 for an example) indicate a measure of events exceeding the quantiles with selected AEPs for various durations. The percentages are based on regional statistics. The total number of stations and the total number of cumulative data years for a given region are provided in the graph title on the PFDS webpage. The graphs also show how the seasonality of precipitation may differ between short-duration and long-duration events in a region.

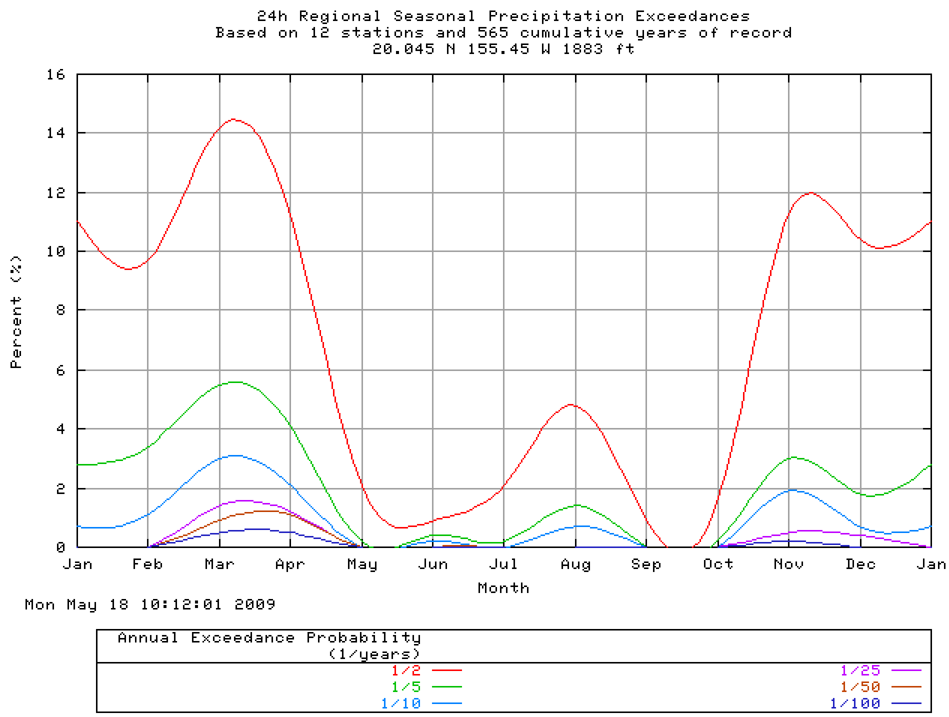
The AEP represents the probability of an event exceeding the corresponding quantile in any given year. Theoretically, 50% of the total number of events in a year could exceed the 1-in-2 AEP quantile, 4% could exceed the 1-in-25 AEP quantile, 2% could exceed the 1-in-50 quantile, and only 1% could exceed the quantile with the 1-in-100 AEP. In other words, for example, the sum of the percentages of all twelve months for the 1-in-2 AEP in the graph is roughly equal to 50%.

Note that seasonality graphs should not be used to derive seasonal precipitation frequency estimates.

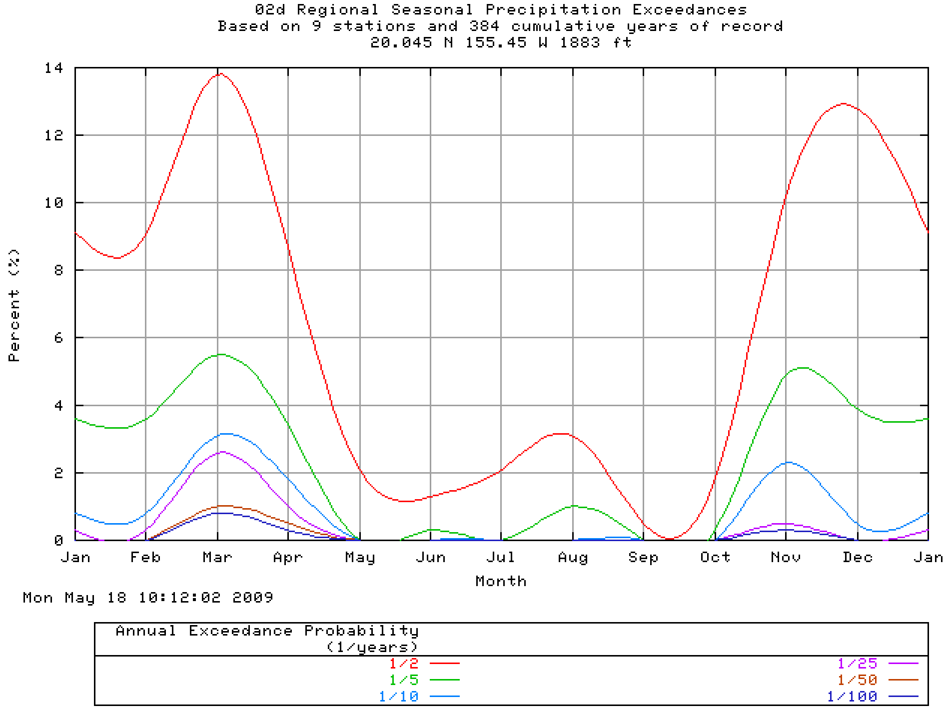
(a) 60-minute duration



(b) 24-hour duration



(c) 2-day duration



(d) 10-day duration

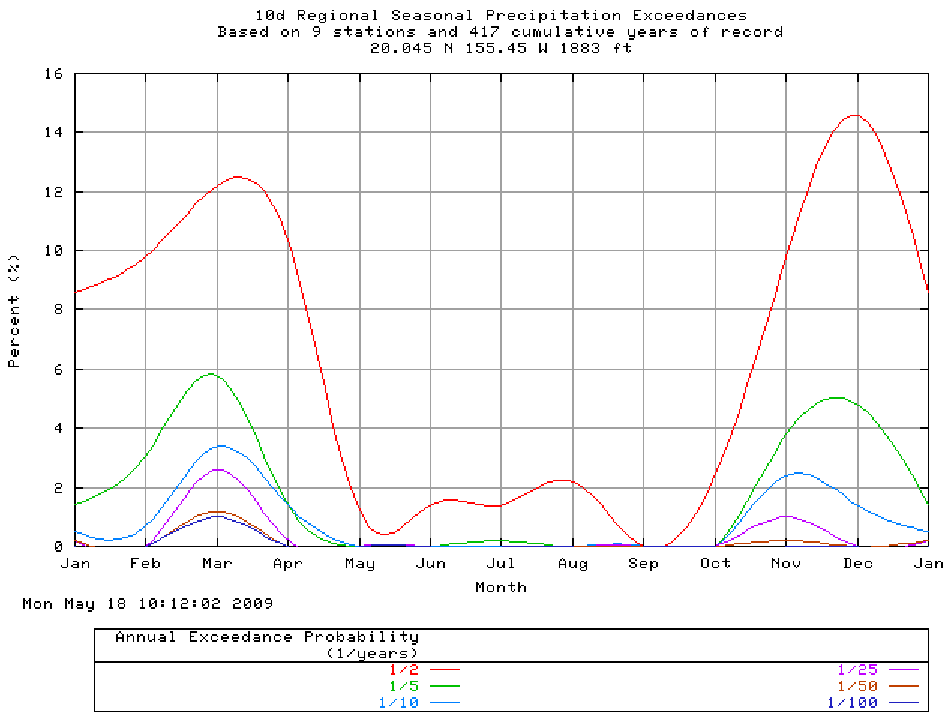


Figure A.2.1. Example of seasonal exceedance graphs for the (a) 60-minute, (b) 24-hour, (c) 2-day, and (d) 10-day durations.

Appendix A.3. Annual maximum series trend analysis

1. Selection of statistical tests for detection of trends in AMS

Precipitation frequency analysis methods used in NOAA Atlas 14 volumes are based on the assumption of stationary climate over the period of observation (and application). To meet the stationarity criterion, the annual maximum series data must be free from trends during the observation period. A number of parametric and non-parametric statistical tests are available for the detection and/or quantification of trends. Selection of an appropriate statistical test requires consideration of the data tested and the limitations of the test.

Annual maximum series (AMS) were first graphed for each station in the project area to examine the time series and to observe general types of trends in the data. Visual inspection of time series plots indicated that there were no abrupt changes or apparent cycles in the AMS, but suggested the possibility of trends at some locations. Changes appeared to be gradual and approximately linear, and both increasing and decreasing trends were observed.

The null hypothesis that there are no trends in annual maximum series was tested on 1-hour and 1-day AMS data. The hypothesis was tested at each station separately and for the region as the whole at the level of significance $\alpha = 5\%$. At-station trends were inspected using the parametric t-test for trend and non-parametric Mann-Kendall test (Maidment, 1993). Both tests are extensively used in environmental science and are appropriate for records that have undergone a gradual change. The tests are fairly robust, readily available, and easy to use and interpret. Since each test is based on different assumptions and different test statistics, the rationale was that if both tests have similar outcomes there can be more confidence about the results. If the outcomes were different, it would provide an opportunity to investigate reasons for discrepancies.

Parametric tests in general have been shown to be more powerful than non-parametric tests when the data are approximately normally distributed and when the assumption of homoscedasticity (homogeneous variance) holds (Hirsch et al., 1991), but are less reliable when those assumptions do not hold. The parametric *t*-test for trend detection is based on linear regression, and therefore checks only for a linear trend in data. However, requiring a linear trend assumption seemed sufficient, since, as mentioned above, time series plots indicated monotonic changes in AMS. The Pearson correlation coefficient (r) was used as a measure of linear association for the *t*-test. The hypothesis that the data are not dependent on time (and also that they are independent and normally distributed numbers) was tested using the test statistic t that follows Student's distribution and is defined as:

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}}$$

where n is the record length of the AMS. The hypothesis is rejected when the absolute value of the computed t value is greater than the critical value obtained from Student's distribution with (n-2) degrees of freedom and exceedance probability of $\alpha/2\%$, where α is the significance level. The sign of the t statistic defines the direction of the trend, positive or negative.

Non-parametric tests have advantages over parametric tests since they make no assumption of probability distribution and are performed without specifying whether trend is linear or nonlinear. They are also more resilient to outliers in data because they do not operate on data directly. Although, one of the disadvantages of non-parametric tests is that they do not account for the magnitude of the data. The Mann-Kendall test has the additional advantage among various non-parametric tests of being able to accommodate missing values in a time series, which was a common occurrence in AMS tested in this project. The test compares the relative magnitudes of annual maximum data.

If annual maximum values are indexed based on time, and x_i is the annual maximum value that corresponds to year t_i, then the Mann-Kendall statistic is given by:

$$S = \sum_{k=1}^{n-1} \sum_{i=k+1}^{n} sign(x_i - x_k)$$

The test statistic *Z* is then computed using a normal approximation and standardizing the statistic *S*. The null hypothesis that there is no trend in the data is rejected at significance level α if the computed *Z* value is greater, in absolute terms, than the critical value obtained from standard normal distribution that has probability of exceedance of α/2%. The sign of the statistic defines the direction of the trend, positive or negative.

In addition to at-station trend analysis, the relative magnitude of any trend in AMS for a region as a whole was assessed by linear regression techniques. Station-specific AMS were rescaled by corresponding mean annual maximum values and they were regressed against time, where time was defined as year of occurrence minus 1900. The regression results from all stations were tested against a null hypothesis of zero serial correlation (zero regression slopes).

2. Trend analysis

The null hypothesis that there are no trends in annual maximum series was tested on 1-day and 1-hour AMS data at each station in the project area with at least 30 years of data. 274 daily stations, and 53 hourly stations satisfied the record length criterion. The *t*-test and Mann-Kendall (MK) test for trends were applied to test the hypothesis. As can be seen from Table A.3.1, results from both tests were essentially the same for both 1-day and 1-hour AMS. For the 1-day duration, tests indicated no statistically-significant trends in approximately 80% of stations tested. In the 20% of stations where trends were detected, almost all of them were negative. For the 1-hour duration, the t-test detected a negative trend at one location; otherwise, no statistically-significant trends were detected by either test. Spatial distribution of trend analysis results for 1-day AMS and 1-hour AMS is shown in Figures A.3.1 and A.3.2., respectively.

Table A.3.1. Trend analysis results based on *t*-test and Mann-Kendall (MK) test for 1-day and 1-hour AMS data.

	1-day AMS		**1-hour AMS**	
	***t*-test**	**MK test**	***t*-test**	**MK test**
Number of stations with no trend	216 (79%)	224 (82%)	52 (98%)	53 (100%)
Number of stations with positive trend	8 (3%)	7 (3%)	0 (0%)	0 (0%)
Number of stations with negative trend	50 (18%)	43 (16%)	1(2%)	0 (0%)
Total number of stations tested	274	274	75	53

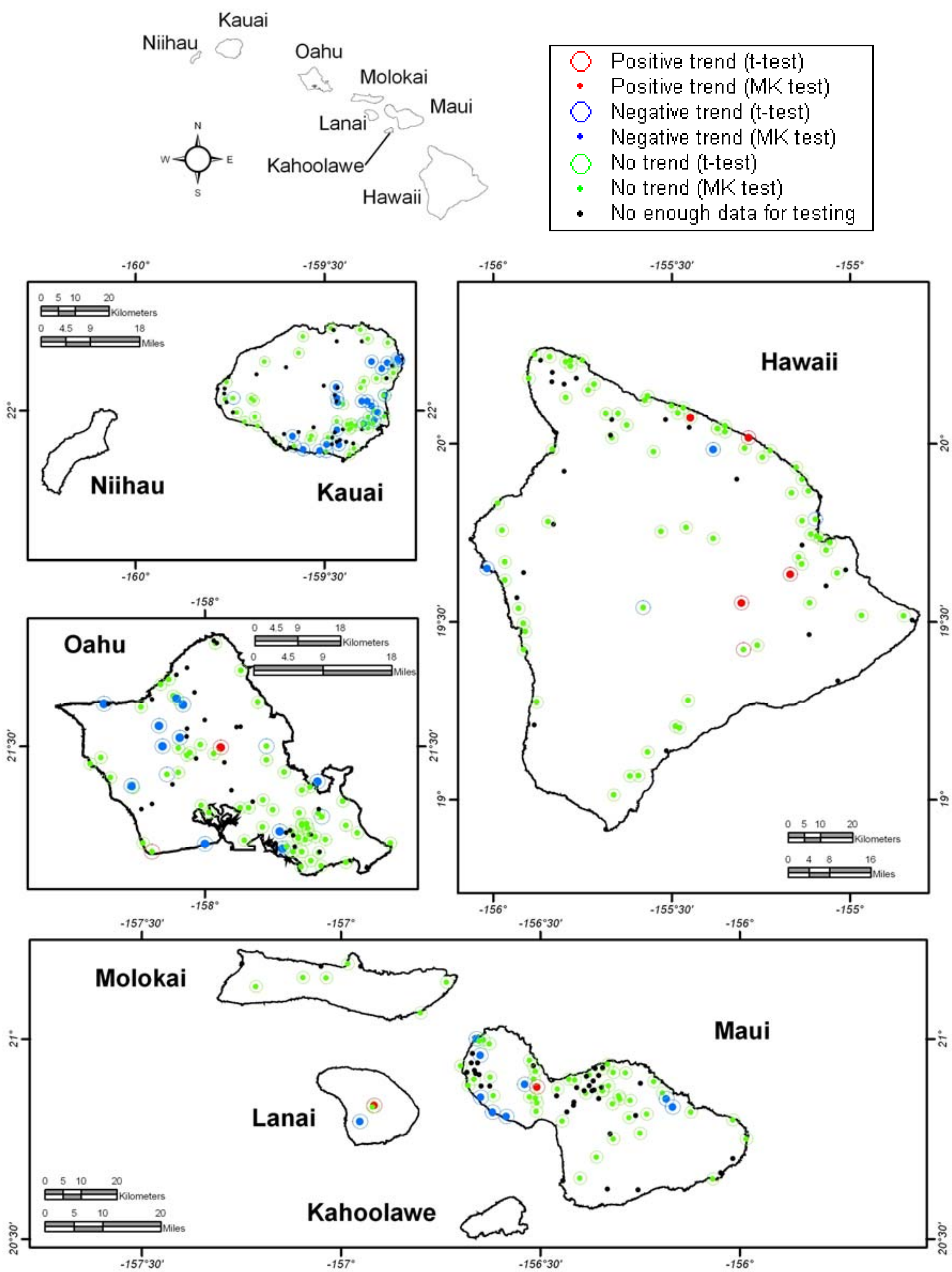


Figure A.3.1. Spatial distribution of trend results for 1-day AMS.

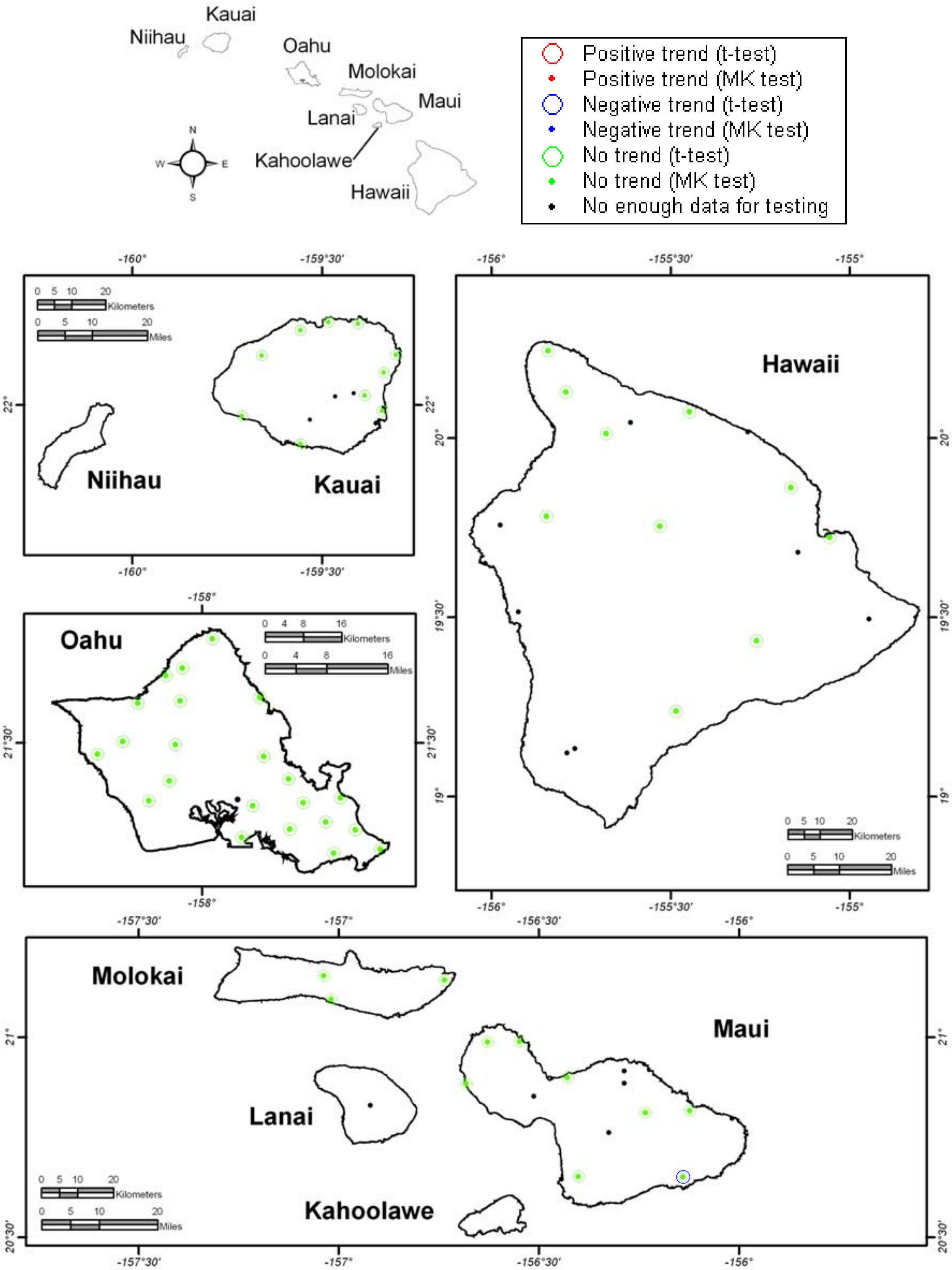


Figure A.3.2. Spatial distribution of trend results for 1-hour AMS.

The relative magnitude of any trend in AMS for the project area as a whole was also assessed by standard linear regression techniques. AMS were rescaled by corresponding mean annual maximum values and then regressed against time (defined as year of occurrence minus 1900). The regression results from all stations as a group were tested against a null hypothesis of zero serial correlation. Results indicated that the null hypothesis (no trends in AMS in the project area) could not be rejected at 5% significance level.

Because all tests indicated little to no statistically-significant trends in the data, the assumption of stationary climate was accepted for this project area and no adjustment to AMS data was recommended.

Appendix A.4 (report was formatted by HDSC)

Final Report
Production of Rainfall Frequency Grids for the Hawaiian Islands Using a Specifically Optimized PRISM System

Prepared for
National Weather Service, Hydrologic Design Service Center
Silver Spring, Maryland

Prepared by
Christopher Daly
PRISM Group
Oregon State University

March 2009

Project Goal

The Hydrometeorological Design Studies Center (HDSC) within the Office of Hydrologic Development of NOAA's National Weather Service is updating precipitation frequency estimates for the Hawaiian Islands. In order to complete the spatial interpolation of point estimates, HDSC requires spatially interpolated grids of MAM precipitation. The contractor, the PRISM Group at Oregon State University (OSU), was tasked with producing a series of grids for rainfall frequency estimation using an optimized system based on the Parameter-elevation Regressions on Independent Slopes Model (PRISM) and HDSC-calculated point estimates for the Hawaiian Islands (HI). The study region excludes the Northwestern Hawaiian Islands (between Kauai and Kure Atoll) because no precipitation data exists for this chain of small islands.

Background

HDSC used the mean annual maximum (MAM), approach as described by Hosking and Wallis in "Regional Frequency Analysis; An Approach Based on L-Moments", 1997, to estimate rainfall frequencies. In this approach, the mean of the underlying rainfall frequency distribution is estimated at point locations with a sufficient history of observations. This mean was originally referred to as the "Index Flood," because early applications of the method were used to analyze flood data in hydrology. The form of the distribution and its parameters are estimated regionally. Once the form of the distribution has been selected and its parameters have been estimated, rainfall frequency estimates can be computed from grids of the MAM. The grids that are the subject of this report are spatially interpolated grids of the point estimates of the MAM for various precipitation durations. The point estimates of the MAM were provided by HDSC. HDSC selected an appropriate rainfall frequency distribution along with regionally estimated parameters and used this information with the grids of the MAM to derive grids of rainfall frequency estimates.

The PRISM Group has previously performed similar work to produce spatially interpolated MAM grids for updates of precipitation frequency estimates in the Semiarid Southwest United States, the Ohio River Basin and Surrounding States, and the Puerto Rico/US Virgin Islands study areas.

This Report

This report describes tasks performed to produce final mean annual maximum (MAM) grids for 14 precipitation durations, ranging from 60 minutes to 60 days, for HI. These tasks were not necessarily performed in this order, nor were they performed just once. The process was dynamic and had numerous feedbacks.

Adapting the PRISM system

The PRISM modeling system was adapted for use in this project after a small investigation was performed for the Semiarid Southwest United States, and subsequently used in the Ohio River Basin and Surrounding States and Puerto Rico/Virgin Islands study areas. This investigation and adaptation procedure is summarized below.

PRISM is a knowledge-based system that uses point data, a digital elevation model (DEM), and many other geographic data sets to generate gridded estimates of climatic parameters (Daly et al. 1994, 2002, 2003, 2006, 2008) at monthly to daily time scales. Originally developed for precipitation estimation, PRISM has been generalized and applied successfully to temperature, among other parameters. PRISM has been used extensively to map precipitation, dew point, and minimum and maximum temperature over the United States, Canada, China, and other countries. Details on PRISM formulation can be found in Daly et al. (2002, 2003, 2008).

Adapting the PRISM system for mapping precipitation frequencies required an approach slightly different than the standard modeling procedure. The amount of station data available to HDSC for precipitation frequency was much less than that available for high-quality precipitation maps, such as the peer-reviewed PRISM 1971-2000 mean precipitation maps (Daly et al. 2008). Data sources suitable for long-term mean precipitation but not for precipitation frequency included snow courses, short-term COOP stations, remote storage gauges, and others. In addition, data for precipitation durations of less than 24 hours were available from hourly rainfall stations only. This meant that mapping precipitation frequency using HDSC stations would sacrifice a significant amount of the spatial detail present in the 1971-2000 mean precipitation maps.

A pilot project to identify ways of capturing more spatial detail in the precipitation frequency maps was undertaken. Early tests showed that mean annual precipitation (MAP) was an excellent predictor of precipitation frequency in a local area, much better than elevation, which is typically used as the underlying, gridded predictor variable in PRISM applications. In these initial tests, the DEM, the predictor grid in PRISM, was replaced by the official USDA digital map of MAP for the lower 48 states (USDA-NRCS 1998, Daly et al. 2000). Detailed information on the creation of the USDA PRISM precipitation grids is available from Daly and Johnson (1999). MAP was found to have superior predictive capability over the DEM for locations in the southwestern US. The relationships between MAP and precipitation frequency were strong because much of the incorporation of the effects of various physiographic features on mean precipitation patterns had already been accomplished with the creation of the MAP grid from PRISM. Preliminary PRISM maps of 2-year and 100-year, 24-hour precipitation were made for the Semiarid Southwest and compared to hand-drawn HDSC maps of the same statistics. Differences were minimal, and mostly related to differences in station data used.

Further investigation found that the square-root transformation of MAP produced somewhat more linear, tighter and cleaner regression functions, and hence, more stable predictions, than the untransformed values; this transformation was incorporated into subsequent model applications. Square-root MAP was a good local predictor of not only longer-duration precipitation frequency statistics, but for short-duration statistics, as well. Therefore, it was determined that a modified PRISM system that used square-root MAP as the predictive grid was suitable for producing high-quality precipitation frequency maps for this project.

For this study, a previously-developed grid of MAP for HI (1971-2000 averages) was used (Figure 1). This grid was developed under funding from the National Park Service.

PRISM Configuration and Operation for the Hawaiian Islands

In general, PRISM interpolation consists of a local moving-window regression function between a predictor grid and station values of the element to be interpolated. The regression function is guided by an encoded knowledge base and inference engine (Daly et al., 2002, 2008). This knowledge base/inference engine is a series of rules, decisions and calculations that set weights for the station data points entering the regression function. In general, a weighting function contains knowledge about an important relationship between the climate field and a geographic or meteorological factor. The inference engine sets values for input parameters by using default values, or it may use the regression function to infer grid cell-specific parameter settings for the situation at hand. PRISM acquires knowledge through assimilation of station data, spatial data sets such as MAP and others, and a control file containing parameter settings.

The other center of knowledge and inference is that of the user. The user accesses literature, previously published maps, spatial data sets, and a graphical user interface to guide the model application. One of the most important roles of the user is to form expectations for the modeled climatic patterns, i.e., what is deemed “reasonable.” Based on knowledgeable expectations, the user selects the station weighting algorithms to be used and determines whether any parameters should be changed from their default values. Through the graphical user interface, the user can click on any grid cell, run the model with a given set of algorithms and parameter settings, view the results graphically, and access a traceback of the decisions and calculations leading to the model prediction.

For each grid cell, the moving-window regression function for MAM vs. MAP took the form

$$\text{MAM value} = \beta_1 * \text{sqrt(MAP)} + \beta_0 \qquad (1)$$

where β_1 is the slope and β_0 is the intercept of the regression equation, and MAP is the grid cell value of mean annual precipitation.

Upon entering the regression function, each station was assigned a weight that is based on several factors. For PRISM MAP mapping (used as the predictor grid in this study), the combined weight of a station was a function of distance, elevation, cluster, vertical layer, topographic facet, coastal proximity, and effective terrain weights, respectively. A full discussion of the general PRISM station weighting functions is available from Daly et al. (2008).

Given that the MAP grid incorporated detailed information about the complex spatial patterns of precipitation, in the Hawaiian Islands, only a subset of these weighting functions was needed for this study. For HI, the combined weight of a station was a function of distance, elevation, cluster, respectively. A station is down-weighted when it is relatively distant or has a much different elevation than the target grid cell, or when it is clustered with other stations (which can lead to over-representation).

The moving-window regression function was populated by station data provided by the HDSC. A PRISM GUI snapshot of the moving-window relationship between MAP and 24-hour MAM in western Maui is shown in Figure 2.

There were little station data available for durations of 12 hours or less from which to perform the interpolation. In addition, it was clear that the spatial patterns of durations of 12 hours or less could be very different than those of durations of 24 hours or more. This issue was encountered in a previous study for Puerto Rico. During that study the following procedure was developed, and adopted here:

(1) Convert available ≤ 12-hour station values to an MAM/24-hr MAM ratio (termed R24) by dividing by the 24-hour values;

(2) using the station R24 data in (1), interpolate R24 values for each ≤ 12-hour duration (60 minutes, and 2, 3, 6, and 12 hours) using PRISM in inverse-distance weighting mode;

(3) using bi-linear interpolation from the cells in the R24 grids from (2), estimate R24 at the location of each station having data for ≥ 24-hour durations only;

(4) multiply the estimated R24 values from (3) by the 24-hour value at each ≥ 24-hour station to obtain estimated ≤ 12-hour values;

(5) append the estimated stations from (4) to the ≤ 12-hour station list to generate a station list that matches the density of that for ≥ 24 hours; and

(6) interpolate MAM values for ≤ 12-hour durations with PRISM, using MAP as the predictor grid.

Investigation of the little available data failed to provide convincing evidence that the spatial patterns of R24 values were strongly affected by MAP, coastal proximity, topographic facets, or other factors. Therefore, the slope of the moving-window regression function for R24 vs. MAP of the form

$$R24 = \beta_1 * \mathrm{sqrt}(MAP) + \beta_0 \quad (2)$$

was forced to zero everywhere. This meant that the interpolated value of R24 was a function of distance and cluster weighting only (essentially inverse-distance weighting).

Relevant PRISM parameters for applications to 60-minute R24 and 24-hour MAM statistics are listed in Tables 1 and 2, respectively. Further explanations of these parameters and associated equations are available in Daly et al. (2002, 2008). Input parameters used for the 60-minute R24 application were generally applied to all durations for which it was applied (less than or equal to 12 hours). The 24-hour MAM input parameters were generally applied to all durations.

The values of radius of influence (*R)*, the minimum number of total (s_t) stations required in the regression were based on information from user assessment via the PRISM graphical user interface, and on a jackknife cross-validation exercise, in which each station was deleted from the data set one at a time, a prediction made in its absence, and mean absolute error statistics compiled (see Results section).

The input parameter that changed readily among the various durations was the default slope (β_{1d}) of the regression function. Slopes are expressed in units that are normalized by the average observed value of the precipitation in the regression data set for the target cell. Evidence gathered during PRISM model development indicates that this method of expression is relatively stable in both space and time (Daly et al. 1994).

Bounds are put on the slopes to minimize unreasonable slopes that might occasionally be generated due to local station data patterns; if the slope is out of bounds and cannot be brought within bounds by the PRISM outlier deletion algorithm, the default slope is invoked (Daly et al., 2002). The maximum slope bound was set to a uniformly high value of 30.0, to accommodate a large range of valid slopes; lower values were not needed to handle extreme values, because all values were within reasonable ranges. Slope default values were based on PRISM diagnostics that provided information on the distribution of slopes across the modeling region. The default value was set to approximate the average regression slope calculated by PRISM. For these applications, default slopes typically increased with increasing duration (Table 3). In general, the longer the duration, the larger the slope. This is primarily a result of higher precipitation amounts at the longer durations, and the tendency for longer-duration MAM statistics to bear a stronger and steeper relationship with MAP than shorter-duration statistics.

Review of Draft Grids

Draft grids for the 60-minute, 12-hour, 24-hour and 10-day durations were produced and made available to HDSC for evaluation. All of the necessary station data were provided by HDSC. The review process was coordinated and undertaken by HDSC in which specific comments, submissions of additional station data information, and the identification of questionable data and spatial patterns were requested. In all, four sets of draft grids were produced during this process.

Most subsequent changes to the draft grids involved omitting and adding stations to the data set, based on map examination and quality control procedures by both the PRISM Group and HDSC. The review process also resulted in two changes to the mapping methodology:

(1) Restriction of the elevation range over which stations are included in the moving-window regression function. In the rain shadow of northwestern Hawaii along the coastline, interpolated MAM was too low, due to an overly steep MAM vs. MAP regression slope calculated from nearby, high-elevation stations. Restricting the upward-looking elevation range to 100 m, but keeping the downward-looking range unrestricted, effectively limited the slope calculation to nearby dry, coastal stations, and produced more reasonable interpolated values.

(2) A revision of the MAP grid to include hourly precipitation station Pohakuloa (COOP ID 51-8063, elevation 1985 m), on the southwest slope of Mauna Kea. Pohakuloa was exhibiting lower MAM values than were reasonable for the gridded MAP for that location. Given that this area was in a steep precipitation gradient, and that the data quality at Pohakuloa appeared to be good, the station was added and the MAP grid re-modeled with PRISM. The resulting grid had a lower MAP in this area, and provided a better match for the MAM values.

Final Grids

Before delivering the final grids to HDSC, the PRISM Group checked them for internal consistency. In other words, the value of the MAM at each grid point for each duration must be less than/or equal to the value for lower durations at the same grid point. If an error of this nature occurs, the current convention is to set the longer duration to a slightly higher value than the lower duration using post-processing tools created by the PRISM Group for previous projects.

The final delivered grids inherited the spatial resolution of the latest 1971-2000 PRISM mean annual precipitation grids for the Hawaiian Islands, which is 15 arc-seconds (~450 meters). The grid cell units are in mm*100. Final MAM grids delivered to HDSC are as follows:

60-minute

120-minute
3-hour
6-hour
12-hour
24-hour
48-hour
4-day
7-day
10-day
20-day
30-day
45-day
60-day

Total: 14

Performance Evaluation

PRISM cross-validation statistics for 60-minute/24-hour MAM ratio and the 60-minute and 24-hour MAM intensities were compiled and summarized in Table 4. These errors were estimated using an omit-one bootstrap method, where each station is omitted from the data set, estimated in its absence, then replaced. Since the 60-minute/24-hour MAM ratio was expressed as a percent, the percent bias and mean absolute error are the given as the bias and MAE in the original percent units (not as a percentage of the percent).

Overall bias and mean absolute error (MAE) were less than 1 percent for the 60-minute/24-hour MAM ratio. For the 60-minute and 24-hour MAM intensities, biases were also very low (< 1 percent), and MAE was slightly less than 10 percent. Errors for 2- to 12-hour durations were similar to those for the 60-minute duration, with biases ranging from 0.5 to 0.8 percent, and MAEs ranging from 9.5 to 9.6 percent. Errors for 2 to 60-day durations were similar to those for the 24-hour duration, with biases ranging from 0.3-1.8 percent, and MAEs from 9.6 to 11.5 percent. Given the lack of data, one would have expected the 60-minute to 12-hour MAM errors to be somewhat higher than those for the 24-hour to 60-day MAMs. A likely reason for this is that the addition of many synthesized stations, derived from a PRISM interpolation of R24 values, resulted in a station data set that was spatially consistent, and thus, somewhat easier to interpolate with each station deleted from the data set. Therefore, there is little doubt that the true interpolation errors for the 60-minute MAM are higher than those shown in Table 4.

References

Barnes, S.L. 1964. A technique for maximizing details in numerical weather map analysis. *Journal of Applied Meteorology,* 3:396-409.

_______. 2006. Guidelines for assessing the suitability of spatial climate data sets. *International Journal of Climatology,* Vol 26: 707-721. http://www.ocs.orst.edu/pub/prism/docs/intjclim06-guidelines-daly.pdf

______, W. P. Gibson, G.H. Taylor, G. L. Johnson, and P. Pasteris. 2002. A knowledge-based approach to the statistical mapping of climate. *Climate Research,* 22: 99-113. http://www.ocs.orst.edu/pub/prism/docs/climres02-kb_approach_statistical_mapping-daly.pdf

_______, Halbleib, M., Smith, J.I., Gibson, W.P., Doggett, M.K., Taylor, G.H., Curtis, J., and Pasteris, P.A. 2008. Physiographically-sensitive mapping of temperature and precipitation across the conterminous United States. *International Journal of Climatology*, 28: 2031-2064. http://prism.oregonstate.edu/pub/prism/docs/intjclim08-physiographic_mapping-daly.pdf

_______, E.H. Helmer, and M. Quinones. 2003. Mapping the climate of Puerto Rico, Vieques, and Culebra. *International Journal of Climatology*, 23: 1359-1381. http://www.ocs.orst.edu/pub/prism/docs/jclim03-map_climate_PR.pdf

_______, R.P. Neilson, and D.L. Phillips, 1994: A Statistical-Topographic Model for Mapping Climatological Precipitation over Mountainous Terrain. *Journal of Applied Meteorology,* 33: 140-158. http://www.ocs.orst.edu/pub/prism/docs/jappclim94-modeling_mountain_precip-daly.pdf

_______, G.H. Taylor, W. P. Gibson, T.W. Parzybok, G. L. Johnson, P. Pasteris. 2000. High-quality spatial climate data sets for the United States and beyond. *Transactions of the American Society of Agricultural Engineers* 43: 1957-1962. http://www.ocs.orst.edu/pub/prism/docs/asae00-spatial_climate_datasets-daly.pdf

USDA-NRCS, 1998. *PRISM Climate Mapping Project--Precipitation. Mean monthly and annual precipitation digital files for the continental U.S.* USDA-NRCS National Cartography and Geospatial Center, Ft. Worth TX. December, CD-ROM.

Table 1. Values of relevant PRISM parameters for interpolation of 60-minute/24-hour mean annual maximum ratio (60-minute R24) for the Hawaiian Islands. See Daly et al. (2002) for details on PRISM parameters.

Name	Description	Value
Regression Function		
R	Radius of influence	5 km*
s_t	Minimum number of total stations desired in regression	15 stations
β_{1m}	Minimum valid regression slope	0.0^+
β_{1x}	Maximum valid regression slope	0.0^+
β_{1d}	Default valid regression slope	0.0^+
Distance Weighting		
A	Distance weighting exponent	2.0
F_d	Importance factor for distance weighting	1.0
D_m	Minimum allowable distance	0.0 km
Elevation Weighting		
B	MAP weighting exponent	NA/NA
F_z	Importance factor for MAP weighting	NA/NA
Δz_m	Minimum station-grid cell MAP difference below which MAP weighting is maximum	NA/NA
Δz_x	Maximum station-grid cell MAP difference above which MAP weight is zero	NA/NA

* Expands to encompass minimum number of total stations desired in regression (s_t).

$^+$ Slopes are expressed in units that are normalized by the average observed value of the precipitation in the regression data set for the target cell. Units here are 1/[sqrt(MAP(mm))*1000].

Table 2. Values of relevant PRISM parameters for modeling of 24-hour mean annual maximum statistics for the Hawaiian Islands. See Daly et al. (2002) for details on PRISM parameters.

Name	Description	Value
Regression Function		
R	Radius of influence	5 km*
s_t	Minimum number of total stations desired in regression	15 stations
β_{1m}	Minimum valid regression slope	0.0+
β_{1x}	Maximum valid regression slope	30.0+
β_{1d}	Default valid regression slope	2.8+
Distance Weighting		
A	Distance weighting exponent	2.0
F_d	Importance factor for distance weighting	1.0
D_m	Minimum allowable distance	0.0 km
Elevation Weighting		
B	Elevation weighting exponent	0.0
F_z	Importance factor for elev weighting	0.0
Δz_m	Minimum station-grid cell elev difference below which MAP weighting is maximum	NA
Δz_x	Maximum station-grid cell elevation difference above which station is eliminated from data set	100 m upwards, 5000 m downwards

* Expands to encompass minimum number of total stations desired in regression (s_t).

+ Slopes are expressed in units that are normalized by the average observed value of the precipitation in the regression data set for the target cell. Units here are 1/[sqrt(MAP(mm))*1000].

Table 3. Values of PRISM slope parameters for modeling of MAM statistics for the Hawaiian Islands for all durations. For durations of 12 hours and below, station data were expressed as the ratio of the given duration's MAM value to the 24-hour MAM value, and interpolated; this was followed by an interpolation of the actual MAM values. See text for details. See Table 1 for definitions of parameters.

	Hawaiian Islands		
Duration	β_{1m}	β_{1x}	β_{1d}
60m/24h ratio	0.0	0.0	0.0
2h/24h ratio	0.0	0.0	0.0
3h/24h ratio	0.0	0.0	0.0
6h/24h ratio	0.0	0.0	0.0
12h/24h ratio	0.0	0.0	0.0
60 minute MAM	0.0	30.0	2.3
2 hour MAM	0.0	30.0	2.3
3 hour MAM	0.0	30.0	2.4
6 hour MAM	0.0	30.0	2.5
12 hour MAM	0.0	30.0	2.7
24 hour MAM	0.0	30.0	2.8
48 hour MAM	0.0	30.0	3.0
4 day MAM	0.0	30.0	3.2
7 day MAM	0.0	30.0	3.6
10 day MAM	0.0	30.0	3.8
20 day MAM	0.0	30.0	4.2
30 day MAM	0.0	30.0	4.5
45 day MAM	0.0	30.0	4.6
60 day MAM	0.0	30.0	4.8

Table 4. PRISM cross-validation errors for 60-minute/24-hour MAM ratio and 24-hour MAM applications to the Hawaiian Islands. Since the 60-minute/24-hour MAM ratio was expressed as a percent, the percent bias and mean absolute error are the given as the bias and MAE in the original percent units (not as a percentage of the percent).

Statistic	N	% Bias	% MAE
60-min/24-hr MAM ratio	79	-0.69	0.69
60-minute MAM	360	0.80	9.63
24-hour MAM	368	0.35	9.66

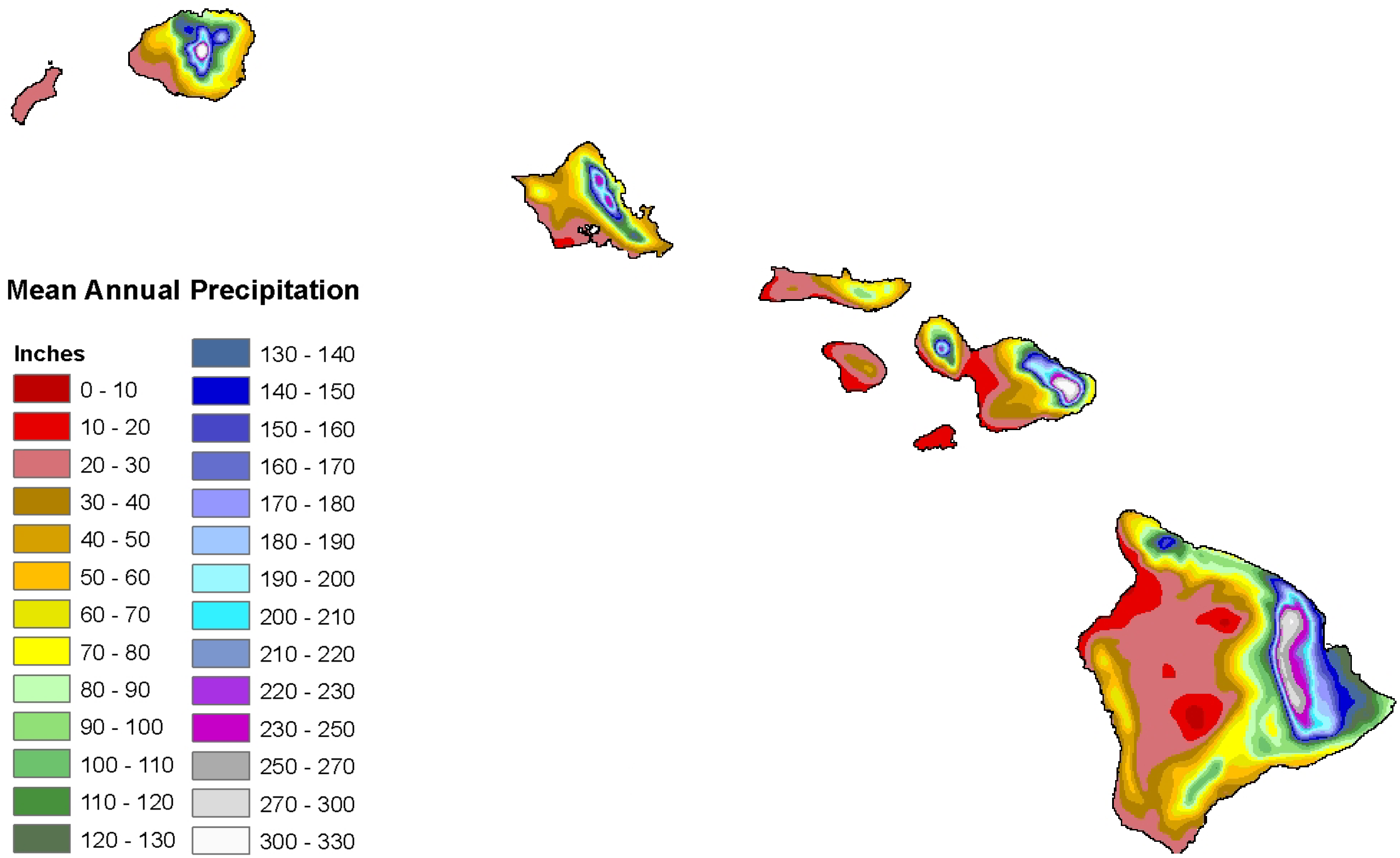


Figure 1. 1971-2000 mean annual precipitation (MAP) grid for the Hawaiian Islands.

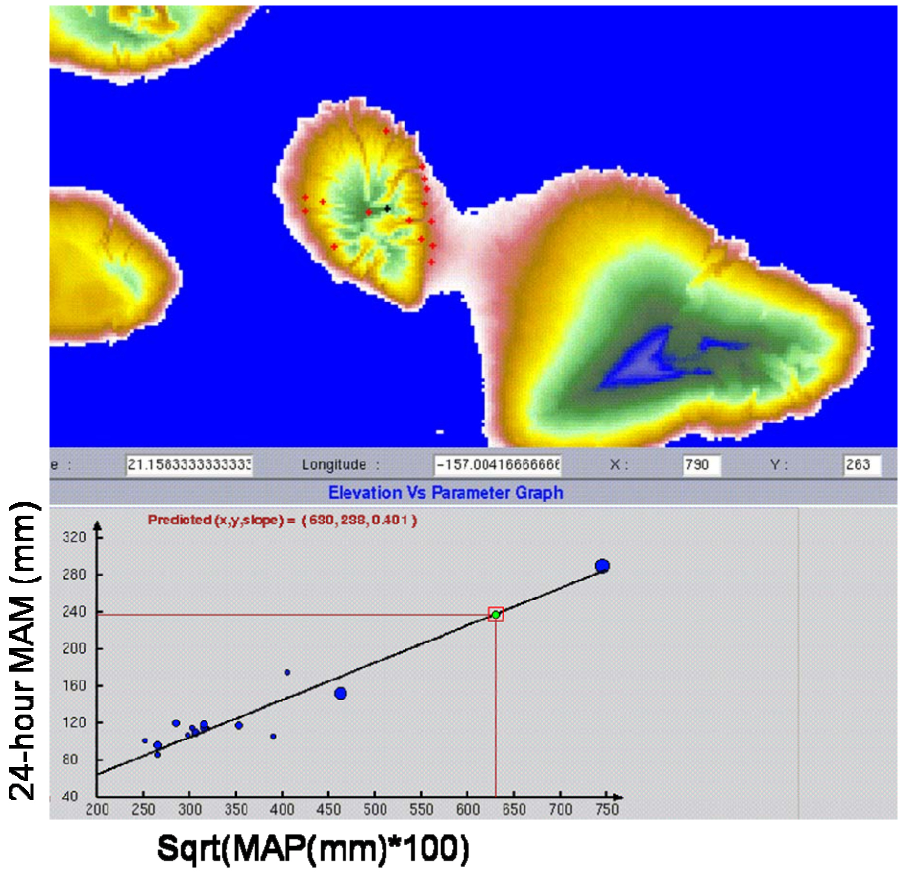


Figure 2. PRISM GUI snapshot of the moving-window relationship between the square root of mean annual precipitation and 24-hour mean annual maximum precipitation (MAM) in western Maui.

Appendix A.5. Peer review comments and responses

The Hydrometeorological Design Studies Center (HDSC) conducted a peer review of the Hawaiian Islands precipitation frequency project during the period September 22, 2008 to October 31, 2008. The review included the following items:

1. AMS-based depth-duration-frequency and intensity-duration-frequency curves at gauged locations;
2. mean annual maximum precipitation maps (60-minute, 12-hour, 24-hour, and 10-day durations);
3. 100-year precipitation frequency maps (60-minute, 12-hour, 24-hour, and 10-day durations);
4. maps showing regional groupings of stations used in frequency analysis for daily durations (≥ 24-hour) and hourly durations (< 24-hour).

HDSC requested comments from approximately 115 individuals. We received 6 responses, some of which represented consolidated feedback from several individuals. This document presents a consolidation of all review comments collected during the 6-week review period and HDSC's responses. Similar issues/comments were grouped together and are accompanied by a single HDSC response. The comments and their respective HDSC responses have been divided into three categories:

1. comments pertaining to regionalization;
2. comments pertaining to mean annual maximum precipitation and precipitation frequency grids/maps;
3. general questions, comments and feedback.

1. Comments pertaining to regionalization

1.1 In some cases, the identified regions appear to include only 1 or 2 stations. It is unclear how the region boundaries were drawn on the basis of such limited data, particularly for durations less than 24 hours.

HDSC response: Homogeneous regions were created based on a variety of statistical tests and climatological considerations. Some regions only comprise of a few stations in order to accurately represent local climate.

1.2 The regional zones look ok following the adjustments since Geoff's visit here.

HDSC response: We agree.

2. Comments pertaining to mean annual maximum precipitation and precipitation frequency grids/maps

2.1 The precipitation frequency maps appear to extend offshore in areas where no data are available. In some cases, the interpolation scheme provides the appearance of detail offshore that may not be justified (see for example the small 3.2 inch contour on the 100-year, 60-minute map of northern Oahu near Mokuleia, or the 8-inch contour on the 100-year, 24-hour map of southern Maui near La Perouse Bay). In these cases, would it be desirable to clip the estimates at the coast?

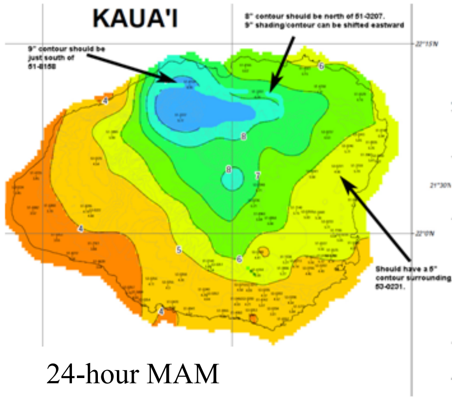
HDSC response: The final maps/grids were masked to match the coastline.

2.2 In general, I don't have any issues with the maximum and minimum values plotted on each map. The east Maui maxima are eye-opening but mainly because they're unexpected to me and not because I don't believe them. If that's what the data show, then that's what it is.

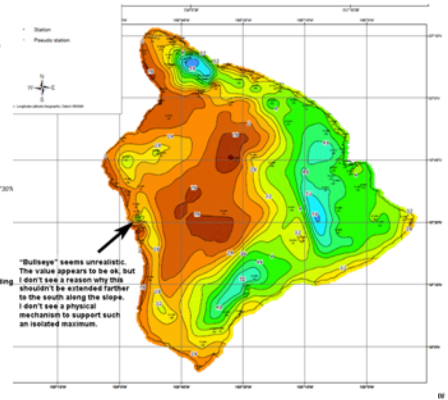
I'm a little concerned about the maximum across eastern Maui. I wouldn't think the rainiest place on Maui would be THAT much rainier than the rainiest place on the Big Island, Oahu or Kauai. For example, at 100y24h there is a max of 38 inches on Maui but only 28 on the big island and 24 on Oahu and Kauai. I'm concerned that lack of data on the other islands is reducing the maximums there. Is it lack of data in critical areas that is keeping the maxes on other Islands lower or are the conditions that different? I don't think the conditions are that different? One could look at types of vegetation on the upslope sides on each of the islands for instance. Is the Halenet data being used for regional growth factors on the other islands? What about the means? This large difference concerns me.

HDSC response: The high values on the eastern slopes and higher terrain of Maui in the peer-reviewed maps were driven by the relatively new Haleakala Climate Network (HaleNet), which consists of climate stations along the leeward and windward slopes of the Haleakala volcano. HaleNet was established in 1988-90 with a number of stations on the relatively dry west-northwest facing (leeward) slope. Then in 1992, additional stations were installed at remote locations along the windward slopes of Haleakala. The records at some of these stations are relatively short. The PRISM mean annual precipitation (MAP) grid, which serves as a predictor layer for the mean annual maximum maps, included the HaleNet stations. Comparatively, although Oahu is surprisingly data sparse on the crest of the windward range, the influence of the MAP grid already contributes to high precipitation frequency (PF) estimates in these areas. The Big Island also has a good deal of un-reported territory as well, so some surprises could exist there; however the 24-hour PF estimates are already higher than those in TP43. We have reviewed the pattern and magnitude of the PF estimates in eastern Maui relative to the other islands and made some changes. Given the short records and disproportionate influence of HaleNet stations on the precipitation frequency spatial patterns due to the lack of stations in general, the decision was made to include only one HaleNet station, Big Bog. We also developed estimates at “pseudo” stations in western Maui and central Kauai to anchor the spatial patterns and magnitudes of the estimates there based on expectations.

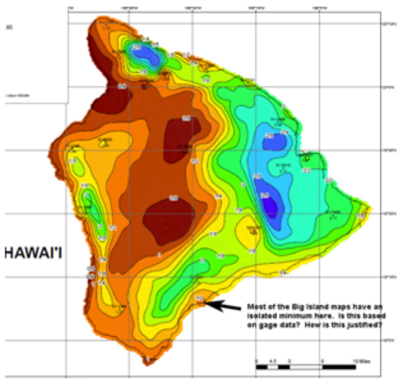
2.4 I noticed there were some quirks with the contouring. For example, there are several instances of max and min "bullseyes" that appear to be based solely on the value from a single gage station. That's fine to me, but there are also instances where the contouring ignores the plotted value at a gage site so there's inconsistency in the convention used. See the images below for examples.



24-hour MAM



100-year 60-minute



60-minute MAM

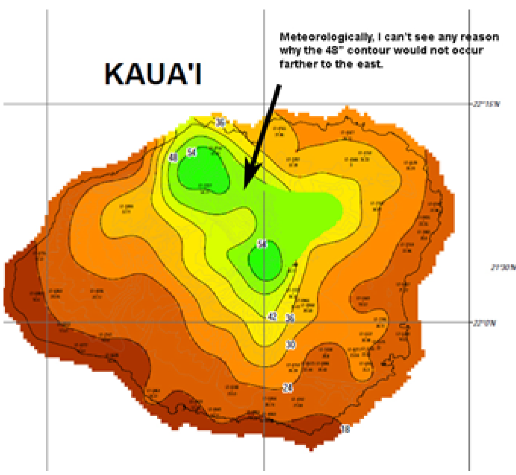
HDSC response: The isolated minimum on the southeastern coast of the Big Island is associated with a minimum on the PRISM mean annual precipitation grid, which was used in the interpolation of the mean annual maxima grids/maps. Although we don't have a gauge for frequency analysis at this location, it is possible PRISM did. Although every attempt is made to ensure the contours are consistent with the plotted station data, there are times when the spatial interpolation deviates to instill climatological consistency and smooth contours. In the final deliverable, the spatially interpolated values at stations are published; it's only during the peer review that the actual gauge-based data are plotted.

The 100-year 60-minute bulls eye on the northern Kona Coast (on the Big Island) is the result of erroneous precipitation frequency estimates at the "pseudo" stations around station 51-3987 (KEALAKEKUA 4 74.8). The "pseudo" stations are locations where hourly PF estimates were developed at daily-only gauge locations to anchor interpolation. This was remedied in the final maps.

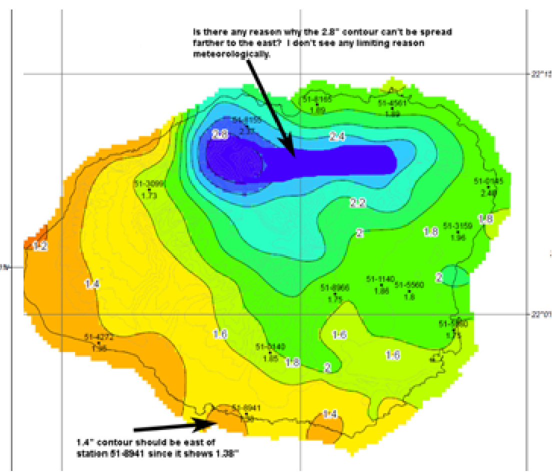
2.4 Many of the precipitation frequency maps appear to include contours over small areas that are apparently influenced heavily by a single station. For example, on the 100-year, 12-hour precipitation map for Oahu, a small contour is drawn near Barbers Point at the southwestern point of the island. In other cases, the small, closed contours contain no stations (see for *example the 42 inch contour on the 100-year, 10-day map for eastern Kauai). Although these contours likely are related to the contouring scheme used, is this amount of detail justified? Is there a way to spatially show the uncertainty in the estimates?*

HDSC response: In areas with few stations, the spatial interpolation is not constrained by nearby stations and therefore can sometimes develop a radius of influence around stations. We tried not to mitigate these issues at the expense of smoothing out spatial detail where we thought it was appropriate (e.g., reliable station, complex terrain). The chosen contouring intervals can also sometimes give a false sense of more variation than exists in reality; we tried our best to identify those cases and to eliminate them. The final precipitation frequency Atlas for the Hawaiian Islands contains upper and lower confidence limits for the point precipitation frequency estimates. We do not depict the uncertainty spatially.

2.5 As indicated in some of the attached graphics, the maxima along the north slope of Kauai appear to be focused too much in the northwest side due to the influence of gage 51-2227. I don't disbelieve maxima at this gage, I just feel the higher values should be extended eastward. I see no meteorological or climatological reason why this wouldn't be the case.



100-year 10-day



60-minute MAM

HDSC response: The lack of reliable data in the remote area of central Kauai has made modeling this area challenging. In response to your comments and an internal investigation, we made two changes to improve estimates in this area. We decided to add a "pseudo" station (station ID 51-6565) to the top of Mt. Waialeale, which is among one of the wettest places on earth. This station didn't have sufficient data to be included in frequency analysis, but based on its limited data, spatially interpolated values, and TP-43/51, we've been able to estimate mean annual maximum and PF estimates for this location. In addition, investigation found that station 51-8155 in north central Kauai near the coast was better regionalized for precipitation frequency analysis in daily region 14 than region 8. These changes improved the spatial patterns in this area so that they are more consistent with expectations.

3 General questions, comments and feedback

3.1 Having a separate web page for each island group is a good idea. However, in the text file saved from each island, the island name is placed where the state name should be.

HDSC response: In the final deliverable we ensured the state name is included in the title.

3.2 I would suggest treating Hawaii different from the other states by having an intermediate web page. For example, from the general US map, if a user selects Hawaii, go to a page with a map of Hawaii. From there, let the user select the particular island of interest. Then go to the island web page.

HDSC response: We created an interim web page for Hawaii on the general PFDS map of the United States. From that page, users can select the specific island they want to visit.

3.3 Web page for Kauai: some of the station symbols (red squares) overlap so much that you cannot see the station name for the underlying symbol. This only occurs in two places (shown by the arrows in the following images).

HDSC response: We recognized the problem. However, that functionality was in place only for the peer review.

3.4 Web page for Oahu: 2.2 Select site from list of stations, stations are suggested to be in alphabetical order.

HDSC response: Stations are now sorted in alphabetical order.

3.5 I think the drafts look good overall and it definitely is great to see the light at the end of the tunnel!

HDSC response: We agree.

3.6 I suggest you remove Molokini Island from the Maui maps. The island is very small and is uninhabited.

HDSC response: Per this suggestion we masked out Molokini Island.

Appendix A.6. List of stations used to prepare precipitation frequency estimates

Table A.6.1. List of daily stations used in the analysis showing station ID, station name, state, island, source of data, latitude, longitude, elevation, period of record and daily precipitation frequency region used to group stations for analysis.

Station ID	Station name	State	Island	Source of data	Latitude	Longitude	Elevation (feet)	Period of record	Daily region
51-0006	AAKUKUI 1007	HI	Kauai	NCDC	21.9500	-159.4333	351	01/1919 - 04/1963	13
51-0033	AHUALOA HOMESTEADS	HI	Hawaii	NCDC	20.0667	-155.5167	2552	01/1919 - 06/1948	10
51-0111	AIEA FIELD 625 761	HI	Oahu	NCDC	21.4167	-157.9500	459	02/1948 - 07/1970	26
51-0115	AIEA FIELD 764A	HI	Oahu	NCDC	21.3833	-157.9333	121	03/1905 - 10/1963	26
51-0119	AIEA FIELD 86 766	HI	Oahu	NCDC	21.3833	-157.9167	312	01/1908 - 12/1960	26
51-0123	AIEA HEIGHTS 764.6	HI	Oahu	NCDC	21.3950	-157.9097	780	12/1976 - 12/2005	26
53-0097	AIHILIANI	HI	Oahu	State	21.3100	-157.8300	205	01/1950 - 12/1976	26
51-0137	ALAKAHI UPPER	HI	Hawaii	NCDC	20.0667	-155.6667	3983	01/1919 - 07/1948	10
53-0251	ALEXANDER RESERVOIR	HI	Kauai	State	21.9550	-159.5283	1610	01/1948 - 01/1975	27
51-0150	AMAUULU 89.2	HI	Hawaii	NCDC	19.7333	-155.1500	1490	01/1953 - 12/1993	11
53-0233	AMP #9	HI	Kauai	State	22.0117	-159.3750	275	01/1948 - 12/1982	9
51-0145	ANAHOLA 1114	HI	Kauai	NCDC	22.1322	-159.3039	180	07/1942 - 11/2001	9
51-0190	AWINI 182.1	HI	Hawaii	NCDC	20.1667	-155.7167	1870	01/1905 - 01/1975	10
51-0242	B Y U LAIE 903.1	HI	Oahu	NCDC	21.6431	-157.9317	20	01/1942 - 07/1999	19
51-0211	BERETANIA PUMP STN 705	HI	Oahu	NCDC	21.3061	-157.8533	20	01/1958 - 12/2005	26
53-0070	BRODIE 2	HI	Oahu	State	21.5186	-158.0347	980	01/1948 - 12/1972	19
51-0240	BRYDESWOOD STA 985	HI	Kauai	NCDC	21.9222	-159.5375	720	04/1910 - 12/2005	27
51-0300	CAMP 84 807	HI	Oahu	NCDC	21.4278	-158.0611	760	01/1956 - 12/1994	19
51-0305	CAMP MOKULEIA 841.16	HI	Oahu	NCDC	21.5806	-158.1825	5	08/1981 - 12/2005	22
51-0248	CAMPBELL IND PK 702.5	HI	Oahu	NCDC	21.3167	-158.1167	10	07/1971 - 12/2005	22
51-0350	COCONUT ISLAND 840.1	HI	Oahu	NCDC	21.4336	-157.7872	15	06/1957 - 11/2005	6
51-0456	EAST LAWAI 934	HI	Kauai	NCDC	21.9097	-159.4939	440	02/1905 - 12/2005	9
51-0470	ELEELE 927	HI	Kauai	NCDC	21.9058	-159.5789	150	01/1905 - 12/2005	27
51-0507	EWA PLANTATION 741	HI	Oahu	NCDC	21.3747	-157.9917	20	01/1905 - 12/2005	22
53-0145	FIELD 102	HI	Maui	State	20.9083	-156.3533	320	11/1952 - 12/1982	25
53-0146	FIELD 105	HI	Maui	State	20.9267	-156.3617	135	11/1952 - 12/1982	25
53-0254	FIELD 130	HI	Kauai	State	21.9083	-159.6167	135	01/1948 - 12/1988	27
53-0148	FIELD 209	HI	Maui	State	20.8833	-156.3767	400	11/1952 - 12/1982	25
53-0166	FIELD 218	HI	Maui	State	20.9367	-156.3300	200	07/1950 - 12/2001	12

Station ID	Station name	State	Island	Source of data	Latitude	Longitude	Elevation (feet)	Period of record	Daily region
53-0168	FIELD 242	HI	Maui	State	20.8833	-156.3283	1160	07/1950 - 12/2001	25
53-0257	FIELD 30	HI	Kauai	State	21.9250	-159.6367	110	01/1948 - 12/1988	27
53-0150	FIELD 301	HI	Maui	State	20.8500	-156.3533	1075	11/1952 - 12/1982	25
53-0152	FIELD 306	HI	Maui	State	20.8700	-156.3700	655	11/1952 - 04/1982	25
53-0169	FIELD 33	HI	Maui	State	20.9950	-156.6533	340	11/1949 - 12/2001	4
53-0256	FIELD 360	HI	Kauai	State	21.9367	-159.6067	470	01/1948 - 12/1988	27
53-0255	FIELD 370	HI	Kauai	State	21.9317	-159.5850	350	01/1948 - 12/1988	27
53-0170	FIELD 46	HI	Maui	State	20.9983	-156.6419	1045	06/1962 - 12/2001	4
51-0541	FIELD 46 474	HI	Maui	NCDC	20.9889	-156.6275	1050	03/1965 - 12/2004	4
53-0154	FIELD 508	HI	Maui	State	20.8700	-156.3900	360	11/1952 - 12/1982	25
53-0258	FIELD 540	HI	Kauai	State	21.9422	-159.5678	775	04/1965 - 12/1988	27
53-0156	FIELD 603	HI	Maui	State	20.8783	-156.4083	205	11/1952 - 04/1982	25
53-0174	FIELD B2	HI	Maui	State	20.9400	-156.6567	825	01/1948 - 12/1972	21
53-0175	FIELD B8	HI	Maui	State	20.9217	-156.6650	675	01/1948 - 12/1972	21
53-0176	FIELD C1	HI	Maui	State	20.9400	-156.6733	325	01/1948 - 12/1972	21
53-0178	FIELD F1	HI	Maui	State	20.9133	-156.6617	900	01/1948 - 12/1972	21
53-0196	FIELD H-18A	HI	Kauai	State	21.9500	-159.4000	260	01/1948 - 12/1973	9
51-0766	GROVE FARM 1021	HI	Kauai	NCDC	21.9667	-159.3833	200	01/1905 - 04/1963	9
51-2146	H S P A EXP STN 707	HI	Oahu	NCDC	21.3000	-157.8333	49	1/1899 - 05/1976	26
51-0832	HAIKU 490	HI	Maui	NCDC	20.9167	-156.3167	489	01/1905 - 12/1969	12
51-0840	HAINA 214	HI	Hawaii	NCDC	20.1000	-155.4667	461	01/1905 - 08/1994	1
51-0905	HAKALAU 142	HI	Hawaii	NCDC	19.9000	-155.1333	160	01/1905 - 01/1994	2
51-0935	HALAULA 1110	HI	Kauai	NCDC	22.1164	-159.3169	253	01/1905 - 10/2000	9
51-0995	HALEAKALA EXP FARM 434	HI	Maui	NCDC	20.8500	-156.3000	2100	01/1910 - 10/1992	25
51-1004	HALEAKALA R S 338	HI	Maui	NCDC	20.7636	-156.2497	6960	03/1939 - 12/2005	28
51-0999	HALEAKALA RANCH 432	HI	Maui	NCDC	20.8372	-156.3189	1890	01/1905 - 12/2005	25
51-1016	HALEHAKU 492.2	HI	Maui	NCDC	20.9158	-156.2864	690	01/1966 - 12/2005	12
51-1038	HALENANAHO 1006	HI	Kauai	NCDC	21.9650	-159.4297	490	07/1942 - 12/2005	13
51-1065	HALEPOHAKU 111	HI	Hawaii	NCDC	19.7644	-155.4589	9260	10/1949 - 12/2005	28
51-1075	HALIIMAILE 423	HI	Maui	NCDC	20.8714	-156.3439	1070	01/1964 - 12/2005	25
51-1086	HAMAKUAPOKO 485	HI	Maui	NCDC	20.9264	-156.3431	320	01/1942 - 12/2005	25
51-1122	HANA 354	HI	Maui	NCDC	20.7500	-155.9865	121	05/1907 - 04/1978	3
51-1125	HANA AIRPORT 355	HI	Maui	NCDC	20.7972	-156.0169	75	12/1950 - 05/2005	3

Station ID	Station name	State	Island	Source of data	Latitude	Longitude	Elevation (feet)	Period of record	Daily region
51-1148	HANAHULI 281	HI	Maui	NCDC	20.7000	-156.0167	331	04/1947 - 04/1976	3
53-0235	HANAMAULU	HI	Kauai	State	21.9950	-159.3583	175	01/1948 - 12/1982	9
51-1195	HANAMAULU 1022	HI	Kauai	NCDC	22.0000	-159.3667	180	01/1905 - 04/1963	9
53-0029	HAWAII AIRPORT	HI	Hawaii	State	20.0450	-155.4500	2075	01/1957 - 12/1979	10
53-0035	HAWAII OFFICE	HI	Hawaii	State	20.0233	-155.6700	2670	01/1948 - 07/1981	20
51-1303	HAWAII VOL NP HQ 54	HI	Hawaii	NCDC	19.4331	-155.2594	3971	06/1905 - 12/2005	15
51-1339	HAWI 168	HI	Hawaii	NCDC	20.2436	-155.8414	580	01/1905 - 12/2005	17
53-0189	HAYASHI	HI	Maui	State	20.8400	-156.5083	340	01/1948 - 12/1994	21
51-1384	HELEMANO INTAKE 881	HI	Oahu	NCDC	21.5500	-158.0000	1270	01/1942 - 04/1979	18
51-1388	HELEMANO RESERVOIR	HI	Oahu	NCDC	21.5333	-158.0333	1030	01/1942 - 04/1963	19
51-1484	HILO 86A	HI	Hawaii	NCDC	19.7269	-155.0884	39	01/1905 - 06/1966	2
51-1492	HILO INTERNATIONAL AP	HI	Hawaii	NCDC	19.7222	-155.0558	38	10/1949 - 12/2005	2
53-0018	HILO SUGAR PLANTATION COM	HI	Hawaii	State	19.7400	-155.0933	100	01/1948 - 12/1979	2
51-1527	HOAEAE UPPER	HI	Oahu	NCDC	21.4500	-158.0500	712	02/1908 - 12/2001	19
51-1557	HOLUALOA 70	HI	Hawaii	NCDC	19.6378	-155.9139	3220	01/1905 - 12/2005	23
51-1701	HONOHINA 137	HI	Hawaii	NCDC	19.9292	-155.1562	300	04/1905 - 12/1993	2
51-1856	HONOKAA TOWN 215	HI	Hawaii	NCDC	20.0850	-155.4825	1080	01/1906 - 12/2005	10
51-1864	HONOKANE 181.1	HI	Hawaii	NCDC	20.1500	-155.7333	801	11/1905 - 01/1975	10
53-0181	HONOKOWAI LUA	HI	Maui	State	20.9500	-156.6750	300	01/1948 - 12/1972	21
51-1914	HONOLUA FIELD 49 494	HI	Maui	NCDC	21.0144	-156.6375	130	07/1907 - 10/2003	4
51-1919	HONOLULU INTL AP 703	HI	Oahu	NCDC	21.3219	-157.9253	7	01/1947 - 12/2005	22
51-1918	HONOLULU OBSERV 702.2	HI	Oahu	NCDC	21.3150	-157.9992	5	08/1962 - 12/2005	22
51-1924	HONOLULU SUBSTATION 407	HI	Oahu	NCDC	21.3167	-157.8667	13	10/1949 - 11/1976	26
51-1930	HONOMANU 450	HI	Maui	NCDC	20.8500	-156.1833	1280	01/1905 - 01/1961	12
51-1955	HONOMU MAKAI 143	HI	Hawaii	NCDC	19.8667	-155.1167	351	01/1921 - 10/1963	2
51-2100	HOOLEHUA 559A	HI	Molokai	NCDC	21.1833	-157.0500	840	06/1926 - 08/1955	5
53-0190	HOPOI RESERVOIR	HI	Maui	State	20.8800	-156.5083	380	01/1948 - 01/1991	21
51-2156	HUEHUE 92.1	HI	Hawaii	NCDC	19.7567	-155.9744	1960	01/1905 - 12/2005	24
51-2161	HUKIPO 945	HI	Kauai	NCDC	21.9828	-159.6831	800	01/1942 - 10/2000	27
53-0191	IAO VALLEY	HI	Maui	State	20.8867	-156.5383	720	11/1949 - 12/1994	18
53-0236	ILIILIULA INTAKE	HI	Kauai	State	22.0400	-159.4717	1070	01/1954 - 12/1982	14
51-2222	ILIILIULA INTAKE 1050	HI	Kauai	NCDC	22.0333	-159.4667	1050	10/1949 - 01/1987	14
51-2227	INTAKE WAINIHA 1086	HI	Kauai	NCDC	22.1528	-159.5681	690	01/1919 - 11/2005	14

Station ID	Station name	State	Island	Source of data	Latitude	Longitude	Elevation (feet)	Period of record	Daily region
53-0080	JACK LANE NURSERY	HI	Oahu	State	21.3367	-157.8467	300	01/1956 - 12/1985	26
53-0200	K-43	HI	Kauai	State	21.9100	-159.4797	250	01/1950 - 12/1973	9
51-2249	KAALA IKI 12	HI	Hawaii	NCDC	19.1333	-155.5667	1342	02/1939 - 12/1978	16
51-2307	KAANAPALI AIRPORT 453.1	HI	Maui	NCDC	20.9457	-156.6933	8	01/1905 - 01/1986	21
53-0161	KAHEKA	HI	Maui	State	20.8950	-156.3667	395	11/1952 - 12/1982	25
51-2552	KAHOMA INTAKE 374	HI	Maui	NCDC	20.9047	-156.6258	2000	01/1919 - 12/2005	18
53-0024	KAHUA RANCH	HI	Hawaii	State	20.1292	-155.7964	3240	01/1948 - 12/2001	20
51-2570	KAHUKU 912	HI	Oahu	NCDC	21.6950	-157.9803	15	01/1905 - 12/2004	19
51-2580	KAHUKU PUMP 2 907	HI	Oahu	NCDC	21.7000	-157.9833	10	01/1942 - 04/1963	19
51-2572	KAHULUI WSO AP 398	HI	Maui	NCDC	20.8997	-156.4286	51	01/1905 - 12/2005	25
51-2595	KAHUNA FALLS 138.2	HI	Hawaii	NCDC	19.8614	-155.1636	1390	05/1911 - 12/2005	11
51-2630	KAILIILI 436	HI	Maui	NCDC	20.8461	-156.2739	2520	03/1925 - 12/2005	12
53-0162	KAILUA	HI	Maui	State	20.8717	-156.3650	695	11/1952 - 12/1982	25
51-2679	KAILUA 446	HI	Maui	NCDC	20.8933	-156.2153	700	01/1905 - 12/2005	12
51-2683	KAILUA FIRE STN 791.3	HI	Oahu	NCDC	21.3961	-157.7394	10	01/1959 - 12/2004	6
51-2686	KAILUA HEIGHTS	HI	Hawaii	NCDC	19.6167	-155.9667	500	01/1928 - 11/1983	23
51-2725	KAIMUKI 715	HI	Oahu	NCDC	21.2833	-157.8000	171	01/1921 - 05/1951	26
51-2751	KAINALIU 73.2	HI	Hawaii	NCDC	19.5369	-155.9289	1500	01/1931 - 12/2005	23
51-2880	KALAE	HI	Hawaii	NCDC	18.9167	-155.6833	39	12/1924 - 04/1949	16
53-0252	KALAHEO	HI	Kauai	State	21.9167	-159.5333	750	01/1950 - 12/1983	27
51-2894	KALAPANA 1 67.8	HI	Hawaii	NCDC	19.3333	-155.0333	10	07/1967 - 07/1989	16
51-2896	KALAUPAPA 563	HI	Molokai	NCDC	21.1900	-156.9831	30	02/1905 - 12/2005	5
51-2960	KALIHI RES SITE 777	HI	Oahu	NCDC	21.3736	-157.8219	910	09/1914 - 12/2005	7
53-0203	KALUAHONO	HI	Kauai	State	21.9167	-159.4417	330	07/1948 - 12/1973	9
51-3054	KAMAOA PUUEO 5.1	HI	Hawaii	NCDC	19.0136	-155.6619	1040	12/1944 - 12/2005	16
51-3077	KAMUELA 192.2	HI	Hawaii	NCDC	20.0167	-155.6667	2671	01/1905 - 03/1980	20
51-3099	KANALOHULUHULU 1075	HI	Kauai	NCDC	22.1297	-159.6586	3600	01/1931 - 12/2005	27
53-0237	KANEHA	HI	Kauai	State	22.1300	-159.3750	845	01/1948 - 12/1982	14
51-3104	KANEHA RESERVOIR 1092	HI	Kauai	NCDC	22.1328	-159.3703	810	11/1963 - 10/2000	14
51-3117	KANEOHE 838.1	HI	Oahu	NCDC	21.4231	-157.8011	60	01/1905 - 12/2005	6
51-3113	KANEOHE MAUKA 781	HI	Oahu	NCDC	21.4167	-157.8167	190	05/1906 - 06/1998	7
51-3159	KAPAA STABLES 1104	HI	Kauai	NCDC	22.0856	-159.3361	175	07/1940 - 12/2004	9
51-3207	KAPAKA	HI	Kauai	NCDC	22.1833	-159.4667	640	01/1919 - 11/1945	14

Station ID	Station name	State	Island	Source of data	Latitude	Longitude	Elevation (feet)	Period of record	Daily region
51-3300	KAPAPALA RANCH 36	HI	Hawaii	NCDC	19.2786	-155.4539	2140	10/1949 - 12/2005	16
51-3367	KAPOHO 93	HI	Hawaii	NCDC	19.5167	-154.8500	190	01/1905 - 01/1960	2
51-3368	KAPOHO BEACH 93.11	HI	Hawaii	NCDC	19.5044	-154.8250	20	07/1975 - 12/2005	2
53-0231	KAUAI EKW#4	HI	Kauai	State	22.0850	-159.3617	335	03/1948 - 12/1982	9
53-0205	KAUAI M & M	HI	Kauai	State	21.9217	-159.4583	300	07/1948 - 12/1973	9
51-3433	KAUAULA INTAKE 375	HI	Maui	NCDC	20.8814	-156.6261	1590	01/1942 - 12/2005	18
51-3461	KAUMALAPAU HARBOR 658	HI	Lanai	NCDC	20.7903	-156.9942	30	05/1963 - 12/2005	21
51-3510	KAUMANA 88.1	HI	Hawaii	NCDC	19.6800	-155.1433	1180	01/1925 - 12/2005	11
51-3734	KAWAIHAPAI 841	HI	Oahu	NCDC	21.5803	-158.1903	40	01/1942 - 12/2001	22
51-3754	KAWAILOA	HI	Oahu	NCDC	21.6167	-158.0833	171	08/1916 - 06/1984	19
53-0115	KAWAILOA 19	HI	Oahu	State	21.5950	-158.0600	660	01/1948 - 12/1983	19
53-0117	KAWAILOA FOREST	HI	Oahu	State	21.5900	-158.0533	710	01/1948 - 12/1983	19
51-3770	KAWAINUI LOWER 193	HI	Hawaii	NCDC	20.0833	-155.6500	1080	01/1919 - 08/1994	10
51-3775	KAWAINUI UPPER	HI	Hawaii	NCDC	20.0833	-155.6833	4081	01/1919 - 07/1948	10
53-0010	KAWELA	HI	Hawaii	State	20.1056	-155.5000	390	01/1955 - 12/1984	1
51-3872	KEAAU 92	HI	Hawaii	NCDC	19.6364	-155.0356	220	01/1905 - 12/2005	2
53-0025	KEAAU ORCHARD	HI	Hawaii	State	19.6453	-155.0111	90	01/1950 - 12/1977	2
51-3911	KE-AHOLE POINT 68.13	HI	Hawaii	NCDC	19.7314	-156.0617	20	02/1981 - 12/2005	24
51-3910	KEAHUA 410	HI	Maui	NCDC	20.8644	-156.3858	480	01/1942 - 12/2005	25
51-3977	KEALAKEKUA 26.2	HI	Hawaii	NCDC	19.4947	-155.9147	1480	01/1905 - 12/2005	23
53-0239	KEALIA	HI	Kauai	State	22.0983	-159.3083	10	01/1948 - 12/1982	9
51-3982	KEALIA 1112	HI	Kauai	NCDC	22.1000	-159.3167	9	01/1905 - 01/1987	9
51-4091	KEANAE 346	HI	Maui	NCDC	20.8294	-156.1681	980	01/1905 - 12/2005	12
51-4163	KEAUHOU 2 73A	HI	Hawaii	NCDC	19.5667	-155.9333	1932	12/1927 - 01/1956	23
51-4250	KEHENA RESERVOIR 176.1	HI	Hawaii	NCDC	20.1667	-155.8000	2523	07/1942 - 04/1968	17
51-4272	KEKAHA 944	HI	Kauai	NCDC	21.9703	-159.7111	9	01/1905 - 12/2004	27
51-4318	KEMOO CAMP 8 855	HI	Oahu	NCDC	21.5386	-158.0864	725	06/1933 - 12/2000	19
53-0011	KIHALANI	HI	Hawaii	State	19.9617	-155.2450	1500	01/1955 - 09/1984	11
51-4489	KIHEI 311	HI	Maui	NCDC	20.7944	-156.4447	160	07/1943 - 12/2005	21
51-4561	KILAUEA 1134	HI	Kauai	NCDC	22.2139	-159.4044	320	01/1905 - 12/2005	8
51-4566	KILAUEA FIELD 17 1135	HI	Kauai	NCDC	22.1833	-159.4000	420	10/1949 - 12/1973	8
51-4620	KIOLAKAA 7	HI	Hawaii	NCDC	19.0667	-155.6167	1050	01/1914 - 04/1953	16
51-4634	KIPAHULU 258	HI	Maui	NCDC	20.6500	-156.0667	259	07/1916 - 04/1981	3

Station ID	Station name	State	Island	Source of data	Latitude	Longitude	Elevation (feet)	Period of record	Daily region
53-0103	KIPAPA	HI	Oahu	State	21.4700	-157.9633	690	01/1960 - 12/1988	19
53-0222	KITANO RESERVOIR	HI	Kauai	State	22.0267	-159.6867	2150	01/1955 - 12/1993	27
51-4660	KOELE 693	HI	Lanai	NCDC	20.8333	-156.9167	1752	01/1905 - 04/1963	5
51-4670	KOHALA 179.1	HI	Hawaii	NCDC	20.2333	-155.7833	312	01/1905 - 03/1971	17
51-4675	KOHALA MAULILI 176	HI	Hawaii	NCDC	20.2167	-155.7833	961	04/1908 - 09/1975	17
51-4680	KOHALA MISSION 175.1	HI	Hawaii	NCDC	20.2294	-155.7961	540	01/1905 - 12/2005	17
51-4735	KOLO 1033	HI	Kauai	NCDC	22.0758	-159.7589	36	08/1936 - 10/2000	27
51-4742	KOLOA 936	HI	Kauai	NCDC	21.9086	-159.4614	240	01/1905 - 12/2005	9
51-4750	KOLOA MAUKA 994	HI	Kauai	NCDC	21.9483	-159.4669	640	01/1905 - 12/2005	13
53-0204	KOLOA MILL	HI	Kauai	State	21.8967	-159.4467	155	07/1948 - 12/1983	9
51-4758	KOLOKO RESERVOIR 1137	HI	Kauai	NCDC	22.1903	-159.3847	490	01/1942 - 12/2005	8
51-4764	KONA AIRPORT 68.3	HI	Hawaii	NCDC	19.6500	-156.0167	30	10/1949 - 08/1981	24
51-4765	KONA VILLAGE 93.8	HI	Hawaii	NCDC	19.8328	-155.9867	20	05/1968 - 12/2005	20
51-4766	KOOLAU DAM 833	HI	Oahu	NCDC	21.4981	-157.9697	1160	01/1919 - 01/1999	18
51-4778	KUALAPUU 534	HI	Molokai	NCDC	21.1539	-157.0369	825	01/1905 - 12/2004	5
51-4815	KUKAIAU 222	HI	Hawaii	NCDC	20.0333	-155.3500	840	01/1905 - 09/1994	1
51-4927	KUKUIHAELE 206.1	HI	Hawaii	NCDC	20.1217	-155.5742	740	01/1905 - 12/2005	1
51-4938	KUKUIHAELE MILL 206	HI	Hawaii	NCDC	20.1292	-155.5665	300	01/1910 - 08/1994	1
51-4950	KUKUIULA 935	HI	Kauai	NCDC	21.8911	-159.4950	100	01/1905 - 12/2005	9
51-5000	KULA BRANCH STN 324.5	HI	Maui	NCDC	20.7617	-156.3242	3050	04/1979 - 12/2005	25
51-5001	KULA EREHWON 328	HI	Maui	NCDC	20.7500	-156.3167	4003	01/1905 - 04/1953	25
51-5004	KULA HOSPITAL 267	HI	Maui	NCDC	20.7042	-156.3592	3004	01/1916 - 12/2005	25
51-5011	KULANI CAMP 79	HI	Hawaii	NCDC	19.5531	-155.3036	5170	10/1947 - 12/2005	15
51-5177	LAHAINA 361	HI	Maui	NCDC	20.8842	-156.6806	40	07/1916 - 10/2001	21
51-5275	LANAI AIRPORT 656	HI	Lanai	NCDC	20.7933	-156.9525	1300	10/1949 - 12/2005	21
51-5286	LANAI CITY 672	HI	Lanai	NCDC	20.8292	-156.9203	1620	01/1930 - 12/2005	5
51-5330	LANIHAU 68.2	HI	Hawaii	NCDC	19.6667	-155.9667	1530	01/1950 - 12/2005	23
51-5404	LAUNIUPOKO INTAKE 376	HI	Maui	NCDC	20.8578	-156.6178	1280	07/1916 - 12/2005	18
51-5408	LAUNIUPOKO VILLAGE 372	HI	Maui	NCDC	20.8547	-156.6489	220	10/1956 - 12/2005	21
53-0065	LEILEHUA	HI	Oahu	State	21.5000	-158.0800	980	01/1948 - 12/2001	19
51-5575	LIHUE 1020	HI	Kauai	NCDC	21.9742	-159.3683	207	01/1905 - 10/2000	9
51-5560	LIHUE VRTY STA 1062.1	HI	Kauai	NCDC	22.0242	-159.3867	380	11/1963 - 12/2004	13
51-5580	LIHUE WSO AP 1020.1	HI	Kauai	NCDC	21.9839	-159.3406	100	02/1950 - 12/2005	9

Station ID	Station name	State	Island	Source of data	Latitude	Longitude	Elevation (feet)	Period of record	Daily region
53-0241	LOT #143	HI	Kauai	State	22.0783	-159.3950	340	03/1948 - 12/1979	13
53-0027	LOWER PIIHONUA	HI	Hawaii	State	19.7150	-155.1333	815	01/1976 - 12/2001	11
51-5637	LUAKAHA LOWER 782	HI	Oahu	NCDC	21.3500	-157.8167	879	01/1905 - 04/1963	14
51-5647	LUALUALEI 804	HI	Oahu	NCDC	21.4214	-158.1353	113	01/1941 - 08/1976	22
51-5665	LUPI UPPER 442	HI	Maui	NCDC	20.8889	-156.2481	1240	01/1919 - 12/2005	12
51-5710	MAHAULEPU 941.1	HI	Kauai	NCDC	21.9000	-159.4211	80	01/1905 - 12/1973	9
53-0206	MAHAULEPU-MEKELUPU	HI	Kauai	State	21.9117	-159.4233	100	07/1948 - 12/1982	9
51-5715	MAHINAHINA 466	HI	Maui	NCDC	20.9594	-156.6506	980	09/1919 - 12/2005	21
51-5721	MAHUKONA 159	HI	Hawaii	NCDC	20.1833	-155.9000	10	04/1912 - 12/1955	17
51-5758	MAKAHA CTRY CLUB 800.3	HI	Oahu	NCDC	21.4783	-158.1964	250	01/1958 - 12/2005	22
51-5766	MAKAHA KAI 796.1	HI	Oahu	NCDC	21.4667	-158.2167	20	07/1942 - 03/1977	22
51-5761	MAKAHALAU 103	HI	Hawaii	NCDC	19.9769	-155.5503	3820	04/1971 - 12/2005	20
51-5792	MAKAPALA NURSERY 181	HI	Hawaii	NCDC	20.1833	-155.7667	1601	02/1925 - 05/1952	17
51-5800	MAKAPUU POINT 724	HI	Oahu	NCDC	21.3135	-157.6519	538	09/1907 - 12/1973	26
51-5864	MAKAWELI 965	HI	Kauai	NCDC	21.9189	-159.6278	140	01/1905 - 12/2005	27
51-5842	MAKENA GOLF CRS 249.1	HI	Maui	NCDC	20.6450	-156.4433	100	05/1982 - 12/2005	21
53-0207	MALUMALU	HI	Kauai	State	21.9533	-159.3833	250	01/1948 - 12/1982	9
51-6055	MALUMALU 1017	HI	Kauai	NCDC	21.9500	-159.3833	249	07/1942 - 04/1963	9
51-6082	MANA 1026	HI	Kauai	NCDC	22.0300	-159.7628	20	01/1905 - 10/2000	27
51-6122	MANOA 712.1	HI	Oahu	NCDC	21.3256	-157.8233	220	01/1905 - 12/2005	18
51-6128	MANOA LYON ARBO 785.2	HI	Oahu	NCDC	21.3331	-157.8025	500	01/1941 - 12/2005	14
51-6130	MANOA TUN 2 716	HI	Oahu	NCDC	21.3283	-157.7914	650	01/1942 - 11/2005	14
51-6134	MANUKA 2	HI	Hawaii	NCDC	19.1131	-155.8289	1760	10/1949 - 12/2005	24
51-6138	MAPULEHU 542	HI	Molokai	NCDC	21.0736	-156.8004	20	07/1906 - 07/1973	5
51-6175	MAULUA 126	HI	Hawaii	NCDC	19.9000	-155.3167	5144	02/1921 - 06/1960	11
51-6190	MAUNA LOA 511	HI	Molokai	NCDC	21.1328	-157.2133	1020	01/1924 - 12/2005	21
51-6198	MAUNA LOA SLOPE OBS 39	HI	Hawaii	NCDC	19.5394	-155.5792	11150	01/1955 - 12/2005	28
53-0246	MIMINO	HI	Kauai	State	22.1117	-159.3483	280	01/1948 - 12/1982	9
53-0104	MOANALUA	HI	Oahu	State	21.3800	-157.8717	340	01/1948 - 12/1988	18
51-6395	MOANALUA 770	HI	Oahu	NCDC	21.3472	-157.8911	20	01/1905 - 12/2005	26
51-6529	MOLOAA 1145	HI	Kauai	NCDC	22.1797	-159.3319	300	06/1929 - 12/2005	8
51-6534	MOLOKAI AP 524	HI	Molokai	NCDC	21.1550	-157.0950	450	10/1949 - 07/2004	21
51-6537	MOLOKOA 1015	HI	Kauai	NCDC	21.9833	-159.3833	200	01/1905 - 12/1973	9

Station ID	Station name	State	Island	Source of data	Latitude	Longitude	Elevation (feet)	Period of record	Daily region
51-6552	MOUNTAIN VIEW 91	HI	Hawaii	NCDC	19.5525	-155.1128	1530	07/1906 - 10/1985	11
51-6888	N WAILUA DITCH 1051	HI	Kauai	NCDC	22.0625	-159.4686	1110	10/1949 - 10/2000	14
51-6588	NAALEHU 14	HI	Hawaii	NCDC	19.0678	-155.5917	800	01/1905 - 12/2005	16
51-6697	NAPOOPOO 28	HI	Hawaii	NCDC	19.4722	-155.9094	400	01/1905 - 12/2005	23
51-6850	NIU RIDGE 1035	HI	Kauai	NCDC	22.0331	-159.7406	1250	01/1942 - 10/2000	27
51-6806	NIULII 179	HI	Hawaii	NCDC	20.2333	-155.7500	79	01/1905 - 09/1975	17
53-0224	NOHILI	HI	Kauai	State	22.0567	-159.7828	215	01/1965 - 12/1993	27
53-0105	NORTH HALAWA	HI	Oahu	State	21.3983	-157.8903	320	07/1953 - 12/1988	18
53-0248	NORTH WAILUA DITCH	HI	Kauai	State	22.0600	-159.4650	1110	01/1954 - 12/1982	14
51-6928	NUUANU RES 4 783	HI	Oahu	NCDC	21.3528	-157.8078	1048	01/1905 - 12/2005	14
51-6933	NUUANU RES 5 775	HI	Oahu	NCDC	21.3389	-157.8364	410	01/1905 - 12/2005	18
53-0063	OHAU FIELD 32	HI	Oahu	State	21.4467	-158.0717	970	01/1948 - 12/2001	19
53-0059	OHAU KU-TREE	HI	Oahu	State	21.4858	-157.9833	1120	01/1948 - 12/1980	18
51-7000	OHE'O 258.6	HI	Maui	NCDC	20.6647	-156.0472	120	02/1982 - 12/2005	3
53-0243	OLD CAMP (M-2B)	HI	Kauai	State	22.1267	-159.3336	410	01/1948 - 12/1982	9
53-0208	OLD G.F. OFFICE	HI	Kauai	State	21.9667	-159.3700	200	01/1948 - 01/1987	9
51-7040	OLINDA #1 332	HI	Maui	NCDC	20.8025	-156.2772	4130	01/1919 - 12/2005	28
51-7059	OLOWALU 296.1	HI	Maui	NCDC	20.8164	-156.6192	30	08/1916 - 12/2005	21
53-0216	OMAO FIELD	HI	Kauai	State	21.9286	-159.4900	525	01/1948 - 12/1983	9
51-7131	OOKALA 223	HI	Hawaii	NCDC	20.0167	-155.2833	430	10/1949 - 09/1993	1
53-0012	OOKALA MAUKA	HI	Hawaii	State	19.9867	-155.2950	1780	01/1955 - 09/1984	10
53-0122	OPAEULA 2	HI	Oahu	State	21.5883	-158.1000	110	01/1948 - 06/1977	22
51-7150	OPAEULA 870	HI	Oahu	NCDC	21.5786	-158.0414	1000	10/1949 - 12/2005	19
51-7166	OPIHIHALE 2 24.1	HI	Hawaii	NCDC	19.2739	-155.8775	1360	05/1956 - 12/2005	24
51-7194	PAAKEA 350	HI	Maui	NCDC	20.8169	-156.1219	1260	01/1905 - 12/2005	12
53-0253	PAANAU	HI	Kauai	State	21.8950	-159.4750	135	02/1951 - 12/1983	9
51-7209	PAAUHAU MAUKA 217.2	HI	Hawaii	NCDC	20.0731	-155.4472	1120	01/1905 - 12/2005	10
51-7312	PAAUILO 221	HI	Hawaii	NCDC	20.0417	-155.3706	800	01/1905 - 12/2005	1
51-7437	PAHALA MAUKA 21.3	HI	Hawaii	NCDC	19.2067	-155.4886	1090	01/1905 - 12/2005	16
51-7457	PAHOA 65	HI	Hawaii	NCDC	19.5178	-154.9669	605	01/1905 - 12/2005	2
53-0163	PAHOLEI	HI	Maui	State	20.8786	-156.3467	855	11/1952 - 04/1982	25
51-7566	PAIA 406	HI	Maui	NCDC	20.9103	-156.3769	170	01/1938 - 12/2005	25
51-7540	PAIKO DRIVE 723.4	HI	Oahu	NCDC	21.2806	-157.7336	10	01/1964 - 12/2005	26

Station ID	Station name	State	Island	Source of data	Latitude	Longitude	Elevation (feet)	Period of record	Daily region
51-7656	PALI GOLF COURSE 788.1	HI	Oahu	NCDC	21.3733	-157.7853	480	01/1905 - 12/2005	7
51-7664	PALOLO VALLEY 718	HI	Oahu	NCDC	21.3233	-157.7719	995	01/1942 - 12/2005	14
51-7711	PAPAIKOU 144.1	HI	Hawaii	NCDC	19.7872	-155.0964	200	01/1905 - 12/2005	2
51-7721	PAPAIKOU MAUKA 140.1	HI	Hawaii	NCDC	19.7833	-155.1333	1285	01/1940 - 01/1990	11
53-0014	PAPPALOA OFFICE	HI	Hawaii	State	19.9800	-155.2233	290	01/1955 - 09/1984	2
53-0209	PAPUAA	HI	Kauai	State	21.9717	-159.4667	550	01/1948 - 05/1984	13
51-7810	PAUOA FLATS 784	HI	Oahu	NCDC	21.3447	-157.8058	1640	01/1942 - 12/2005	14
53-0182	PEDRO CAMP	HI	Maui	State	20.9633	-156.6700	450	01/1948 - 12/1972	21
51-8000	PEPEEKEO MAKAI 144	HI	Hawaii	NCDC	19.8500	-155.0861	102	10/1949 - 02/1972	2
51-8155	PH WAINIHA 1115	HI	Kauai	NCDC	22.1961	-159.5561	101	01/1938 - 12/2005	14
53-0171	PIIHOLO	HI	Maui	State	20.8567	-156.3033	1780	01/1948 - 12/2001	25
53-0066	POAMOHO	HI	Oahu	State	21.5167	-158.0467	940	01/1948 - 12/2001	19
51-8060	POHAKEA BRIDGE 307.2	HI	Maui	NCDC	20.8186	-156.5100	170	01/1942 - 12/2005	21
51-8063	POHAKULOA 107	HI	Hawaii	NCDC	19.7528	-155.5294	6511	10/1949 - 12/2004	28
51-8165	PRINCEVILLE RANCH 1117	HI	Kauai	NCDC	22.2181	-159.4828	217	06/1938 - 12/2005	8
51-8181	PUAKEA RANCH	HI	Hawaii	NCDC	20.2333	-155.8667	600	01/1905 - 12/1933	17
51-8186	PUAKO 95.1	HI	Hawaii	NCDC	19.9833	-155.8333	49	11/1939 - 01/1976	20
51-8205	PUEHU RIDGE 1040	HI	Kauai	NCDC	22.0322	-159.6928	1600	08/1939 - 10/2000	27
51-8217	PUHI 1013	HI	Kauai	NCDC	21.9656	-159.3964	329	01/1935 - 12/2005	9
51-8310	PUNALUU 884	HI	Oahu	NCDC	21.5833	-157.9000	39	01/1906 - 04/1971	19
51-8316	PUNCHBOWL CRATER 709	HI	Oahu	NCDC	21.3103	-157.8458	360	02/1950 - 12/2005	26
53-0086	PUPUKEA ALAPIO	HI	Oahu	State	21.6483	-158.0336	540	01/1977 - 12/2001	19
51-8500	PUU MANAWAHUA 725.6	HI	Oahu	NCDC	21.3814	-158.1197	1673	01/1977 - 05/2005	22
51-8550	PUU OO	HI	Hawaii	NCDC	19.7333	-155.3833	6345	01/1910 - 01/1975	15
51-8555	PUU WAAWAA 94.1	HI	Hawaii	NCDC	19.7811	-155.8458	2520	10/1949 - 12/2004	20
51-8352	PUUHI 940	HI	Kauai	NCDC	21.8833	-159.4333	79	01/1907 - 04/1963	9
51-8552	PUUHONUA-O-HONAUNAU 27.4	HI	Hawaii	NCDC	19.4214	-155.9139	15	11/1970 - 12/2005	24
51-8422	PUUKOHOLA HEIAU 98.1	HI	Hawaii	NCDC	20.0297	-155.8231	140	01/1977 - 12/2005	20
51-8398	PUUKOLII 457	HI	Maui	NCDC	20.9167	-156.6833	361	01/1942 - 12/1972	21
53-0225	PUULUA RESERVOIR	HI	Kauai	State	22.0953	-159.6797	3250	01/1965 - 10/1993	27
51-8543	PUUNENE 396	HI	Maui	NCDC	20.8747	-156.4569	60	01/1944 - 12/2005	21
53-0212	PUUOHEWA	HI	Kauai	State	21.9283	-159.4783	500	07/1948 - 12/1973	9
51-8549	PUU-O-HOKU RANCH 542.1	HI	Molokai	NCDC	21.1436	-156.7347	700	01/1955 - 10/2005	5

Station ID	Station name	State	Island	Source of data	Latitude	Longitude	Elevation (feet)	Period of record	Daily region
51-8548	PUUOKUMAU 167	HI	Hawaii	NCDC	20.2000	-155.8333	1801	01/1942 - 03/1971	17
53-0041	PUUWAAWAA RANCH	HI	Hawaii	State	19.7733	-155.8300	3450	01/1956 - 12/1997	20
53-0192	RESERVOIR #1	HI	Maui	State	20.8550	-156.5267	1100	11/1949 - 12/1993	18
53-0213	RESERVOIR #5	HI	Kauai	State	21.9600	-159.4167	285	01/1948 - 02/1996	13
51-8573	RESERVOIR 6 1004	HI	Kauai	NCDC	21.9500	-159.4500	420	10/1949 - 12/1973	13
51-8638	S GLENWOOD 91.8	HI	Hawaii	NCDC	19.4633	-155.1139	2060	05/1980 - 11/2003	11
51-8600	SEA MOUNTAIN 12.15	HI	Hawaii	NCDC	19.1367	-155.5142	80	06/1982 - 12/2005	16
53-0099	SPIELGELBERGER	HI	Oahu	State	21.3233	-157.8100	320	01/1948 - 12/1991	18
51-8688	SPRECKELSVILLE 400	HI	Maui	NCDC	20.8972	-156.4131	90	01/1943 - 12/2005	25
51-8601	ST STEPHEN'S SEMINARY	HI	Oahu	NCDC	21.3667	-157.7786	448	01/1947 - 12/1996	7
53-0172	STATION 423	HI	Maui	State	20.8700	-156.3433	1070	01/1948 - 12/2001	25
51-8718	SUGAHARA CAMP	HI	Hawaii	NCDC	20.0500	-155.3500	259	01/1905 - 09/1984	1
51-8738	TANTALUS 2 780.5	HI	Oahu	NCDC	21.3283	-157.8236	1330	01/1905 - 12/2005	18
51-8805	U S MAGNETIC OBSERVATORY	HI	Oahu	NCDC	21.3000	-158.1000	10	01/1905 - 06/1960	22
51-8750	UKUMEHAME 301	HI	Maui	NCDC	20.8058	-156.5853	80	01/1942 - 09/1999	21
51-8760	ULUPALAKUA RANCH 250	HI	Maui	NCDC	20.6519	-156.4008	1900	01/1955 - 12/2005	25
51-8780	UMIKOA 118	HI	Hawaii	NCDC	19.9833	-155.3833	3422	02/1921 - 01/1976	10
51-8815	UNIV OF HAWAII 713	HI	Oahu	NCDC	21.3000	-157.8167	79	11/1925 - 12/2005	26
51-8830	UPOLU POINT USCG 159.2	HI	Hawaii	NCDC	20.2500	-155.8833	61	05/1956 - 12/1992	17
51-8838	UPPER WAHIAWA 874.3	HI	Oahu	NCDC	21.5031	-158.0083	1045	01/1948 - 12/2005	18
53-0016	UWEKAHUNA (HVO)	HI	Hawaii	State	19.4217	-155.2978	4050	01/1955 - 12/2001	15
51-8941	WAHIAWA 930	HI	Kauai	NCDC	21.8967	-159.5569	215	01/1905 - 12/2005	27
51-8945	WAHIAWA DAM 863	HI	Oahu	NCDC	21.4967	-158.0497	854	01/1940 - 12/2004	19
51-8955	WAHIKULI 364	HI	Maui	NCDC	20.9000	-156.6656	580	01/1943 - 10/2001	21
51-8958	WAIAHI LOWER 1054	HI	Kauai	NCDC	22.0167	-159.4500	565	05/1936 - 01/1987	14
51-8966	WAIAHI UPPER 1052	HI	Kauai	NCDC	22.0219	-159.4644	780	01/1943 - 12/2004	14
51-8964	WAIAHOLE 837	HI	Oahu	NCDC	21.4705	-157.8836	745	01/1942 - 12/2005	14
51-9014	WAIAKEA 88	HI	Hawaii	NCDC	19.6333	-155.1667	1923	01/1905 - 12/1952	11
51-9020	WAIAKEA MILL	HI	Hawaii	NCDC	19.7000	-155.0667	49	01/1905 - 12/1988	2
51-9025	WAIAKEA SCD 88.2	HI	Hawaii	NCDC	19.6614	-155.1350	1050	01/1953 - 12/2005	11
51-9185	WAIALAE KAHALA 715	HI	Oahu	NCDC	21.2733	-157.7803	10	01/1938 - 12/2005	26
51-9195	WAIALUA 847	HI	Oahu	NCDC	21.5744	-158.1206	32	01/1908 - 12/2004	22
51-9231	WAIANAE 798	HI	Oahu	NCDC	21.4406	-158.1786	50	01/1905 - 12/2005	22

Station ID	Station name	State	Island	Source of data	Latitude	Longitude	Elevation (feet)	Period of record	Daily region
51-9253	WAIAWA 943	HI	Kauai	NCDC	21.9944	-159.7314	10	01/1905 - 10/2000	27
51-9275	WAIEHU CAMP 484	HI	Maui	NCDC	20.9189	-156.5125	320	09/1944 - 12/2005	4
51-9303	WAIHEE 483	HI	Maui	NCDC	20.9333	-156.5167	220	08/1916 - 12/1994	4
51-9281	WAIHEE 837.5	HI	Oahu	NCDC	21.4508	-157.8500	110	07/1942 - 12/2005	7
51-9315	WAIHEE VALLEY 482	HI	Maui	NCDC	20.9472	-156.5264	300	07/1942 - 12/2005	4
51-9332	WAIKAMOI 449	HI	Maui	NCDC	20.8647	-156.1928	1200	01/1907 - 12/2005	12
51-9335	WAIKAMOI DAM 336	HI	Maui	NCDC	20.8122	-156.2328	4320	10/1949 - 12/2004	12
51-9340	WAIKANE 885	HI	Oahu	NCDC	21.5000	-157.8833	760	01/1921 - 11/1982	14
51-9376	WAIKAPU 390	HI	Maui	NCDC	20.8522	-156.5122	425	08/1916 - 12/2004	21
51-9397	WAIKIKI 717.2	HI	Oahu	NCDC	21.2722	-157.8181	10	08/1919 - 12/2005	26
51-9142	WAIKOLOA 95.8	HI	Hawaii	NCDC	19.9222	-155.8006	880	07/1975 - 12/2005	20
51-9467	WAILUA KAI 1065	HI	Kauai	NCDC	22.0403	-159.3403	50	01/1948 - 10/2000	9
53-0250	WAILUA-UKA	HI	Kauai	State	22.0250	-159.4017	250	01/1948 - 12/1982	13
51-9484	WAILUKU 386	HI	Maui	NCDC	20.8997	-156.5156	540	10/1949 - 11/2002	4
51-9521	WAIMANALO 794	HI	Oahu	NCDC	21.3500	-157.7333	59	01/1905 - 08/1969	6
51-9534	WAIMANALO EXP F 795.1	HI	Oahu	NCDC	21.3356	-157.7119	60	09/1969 - 11/2005	6
51-9593	WAIMEA 892	HI	Oahu	NCDC	21.6261	-158.0678	330	01/1915 - 12/2004	19
51-9629	WAIMEA 947	HI	Kauai	NCDC	21.9592	-159.6758	20	10/1949 - 12/2005	27
51-9603	WAIMEA ARBORETUM 892.2	HI	Oahu	NCDC	21.6356	-158.0536	40	01/1979 - 12/2005	19
53-0004	WAIMEA RESERVOIR	HI	Hawaii	State	20.0517	-155.6250	2790	01/1961 - 12/2001	20
53-0020	WAINAKU CAMP2 145	HI	Hawaii	State	19.7450	-155.1100	500	01/1948 - 12/1987	2
51-9765	WAIOPAI RANCH 256	HI	Maui	NCDC	20.6336	-156.2072	220	01/1905 - 12/2005	25
51-9955	WEST LAWAI 931	HI	Kauai	NCDC	21.8939	-159.5128	210	01/1905 - 12/2005	9
51-9795	WHEELER AAF 810.1	HI	Oahu	NCDC	21.4872	-158.0281	820	01/1905 - 12/1970	19
51-9800	WHEELER AAF 810.1	HI	Oahu	NCDC	21.4833	-158.0333	846	01/1939 - 12/1980	19
51-9980	WILHELMINA RISE 721	HI	Oahu	NCDC	21.2989	-157.7847	1100	01/1938 - 12/2005	26

Table A.6.2. Lists of hourly stations used in the analysis showing station ID, station name, state, island, source of data, latitude, longitude, elevation, period of record and daily and hourly precipitation frequency region used to group stations for analysis.

Station ID	Station name	State	Island	Source of data	Latitude	Longitude	Elevation (feet)	Period of record	Daily region	Hourly region
51-0055	AHUIMANU LOOP 839.12	HI	Oahu	NCDC	21.4319	-157.8372	240	09/1968 - 12/2005	7	3
51-0140	ALEXANDER RESV 983	HI	Kauai	NCDC	21.9600	-159.5319	1610	03/1965 - 10/1997	27	5
51-0145	ANAHOLA 1114	HI	Kauai	NCDC	22.1322	-159.3039	180	03/1965 - 11/2001	9	4
51-0300	CAMP 84 807	HI	Oahu	NCDC	21.4278	-158.0611	760	05/1965 - 12/2005	19	7
51-0404	DOWSETT 775.4	HI	Oahu	NCDC	21.3372	-157.8344	390	06/1965 - 12/2005	18	5
51-0541	FIELD 46 474	HI	Maui	NCDC	20.9889	-156.6275	1050	03/1965 - 11/2005	4	2
51-0964	HALAWA SHAFT 771.2	HI	Oahu	NCDC	21.3811	-157.9042	170	04/1965 - 12/2005	26	7
51-1016	HALEHAKU 492.2	HI	Maui	NCDC	20.9158	-156.2864	690	01/1966 - 03/1989	12	2
51-1125	HANA AIRPORT 355	HI	Maui	NCDC	20.7972	-156.0169	75	03/1979 - 07/2005	3	2
51-1140	HANAHANAPUNI 1055.2	HI	Kauai	NCDC	22.0303	-159.4158	580	07/1977 - 12/2005	13	5
51-1308	HAWAII KAI G.C. 724.19	HI	Oahu	NCDC	21.2992	-157.6647	21	05/1965 - 12/2005	26	7
51-1303	HAWAII VOL NP HQ 54	HI	Hawaii	NCDC	19.4331	-155.2594	3971	03/1965 - 12/2005	15	6
51-1339	HAWI 168	HI	Hawaii	NCDC	20.2436	-155.8414	580	03/1965 - 12/2005	17	8
51-1385	HAW'N OCN VIEW EST 3.9	HI	Hawaii	NCDC	19.1222	-155.7886	2900	08/1980 - 12/2005	24	8
51-1492	HILO INTERNATIONAL AP	HI	Hawaii	NCDC	19.7222	-155.0558	38	10/1962 - 12/2005	2	1
51-1540	HOKULOA 725.2	HI	Oahu	NCDC	21.3906	-158.0997	2260	05/1965 - 12/2005	22	10
51-1919	HONOLULU INTL AP 703	HI	Oahu	NCDC	21.3219	-157.9253	7	10/1962 - 12/2005	22	10
51-2156	HUEHUE 92.1	HI	Hawaii	NCDC	19.7567	-155.9744	1960	03/1986 - 12/2005	24	8
51-2453	KAHAKULOA MAUKA 482.3	HI	Maui	NCDC	20.9892	-156.5478	650	12/1967 - 12/2005	4	2
51-2600	KAHUA RANCH HQTRS 176.3	HI	Hawaii	NCDC	20.1275	-155.7914	3240	03/1965 - 12/2005	20	8
51-2570	KAHUKU 912	HI	Oahu	NCDC	21.6950	-157.9803	15	05/1965 - 12/2005	19	3
51-2572	KAHULUI WSO AP 398	HI	Maui	NCDC	20.8997	-156.4286	51	10/1962 - 12/2005	25	9
51-2595	KAHUNA FALLS 138.2	HI	Hawaii	NCDC	19.8614	-155.1636	1390	03/1965 - 12/2005	11	1
51-2683	KAILUA FIRE STN 791.3	HI	Oahu	NCDC	21.3961	-157.7394	10	05/1965 - 12/2005	6	3
51-3072	KAMUELA 1 201.2	HI	Hawaii	NCDC	20.0428	-155.6111	2880	06/1981 - 12/2005	20	8
51-3099	KANALOHULUHULU 1075	HI	Kauai	NCDC	22.1297	-159.6586	3600	03/1965 - 12/2005	27	5
51-3159	KAPAA STABLES 1104	HI	Kauai	NCDC	22.0856	-159.3361	175	01/1966 - 12/2005	9	4
51-3510	KAUMANA 88.1	HI	Hawaii	NCDC	19.6800	-155.1433	1180	03/1965 - 12/2005	11	1
51-3547	KAUNAKAKAI MAU 536.5	HI	Molokai	NCDC	21.0950	-157.0178	70	04/1965 - 12/2005	21	9
51-3562	KAUPAKULUA 435.3	HI	Maui	NCDC	20.8847	-156.2864	1400	12/1988 - 12/2005	12	2
51-3576	KAUPO RANCH 259	HI	Maui	NCDC	20.6514	-156.1386	1020	03/1965 - 12/2005	25	6

Station ID	Station name	State	Island	Source of data	Latitude	Longitude	Elevation (feet)	Period of record	Daily region	Hourly region
51-3925	KEAIWA CAMP 22.1	HI	Hawaii	NCDC	19.2386	-155.4839	1700	03/1965 - 12/2005	16	6
51-3987	KEALAKEKUA 4 74.8	HI	Hawaii	NCDC	19.5136	-155.9244	1420	05/1978 - 12/2005	23	8
51-4272	KEKAHA 944	HI	Kauai	NCDC	21.9703	-159.7111	9	03/1965 - 12/2005	27	10
51-4561	KILAUEA 1134	HI	Kauai	NCDC	22.2139	-159.4044	320	02/1966 - 12/2005	8	4
51-4778	KUALAPUU 534	HI	Molokai	NCDC	21.1539	-157.0369	825	04/1965 - 12/2005	5	2
51-5000	KULA BRANCH STN 324.5	HI	Maui	NCDC	20.7617	-156.3242	3050	05/1977 - 12/2005	25	6
51-5177	LAHAINA 361	HI	Maui	NCDC	20.8842	-156.6806	40	03/1965 - 10/2001	21	9
51-5260	LALAMILO FLD OF 191.1	HI	Hawaii	NCDC	20.0117	-155.6797	2615	03/1965 - 12/2005	20	8
51-5286	LANAI CITY 672	HI	Lanai	NCDC	20.8292	-156.9203	1620	11/1976 - 12/2005	5	2
51-5560	LIHUE VRTY STA 1062.1	HI	Kauai	NCDC	22.0242	-159.3867	380	03/1965 - 12/2005	13	5
51-5580	LIHUE WSO AP 1020.1	HI	Kauai	NCDC	21.9839	-159.3406	100	10/1962 - 12/2005	9	4
51-5655	LULUKU 781.7	HI	Oahu	NCDC	21.3875	-157.8094	280	05/1967 - 12/2005	7	5
51-5758	MAKAHA CTRY CLUB 800.3	HI	Oahu	NCDC	21.4783	-158.1964	250	03/1966 - 12/2005	22	10
51-5842	MAKENA GOLF CRS 249.1	HI	Maui	NCDC	20.6450	-156.4433	100	07/1982 - 12/2005	21	9
51-6222	MAUNAWILI 787.1	HI	Oahu	NCDC	21.3508	-157.7667	395	04/1965 - 12/2005	7	3
51-6553	MOUNT KAALA 844	HI	Oahu	NCDC	21.5025	-158.1489	4025	05/1965 - 12/2005	22	10
51-7131	OOKALA 223	HI	Hawaii	NCDC	20.0167	-155.2833	430	07/1978 - 10/1993	1	1
51-7150	OPAEULA 870	HI	Oahu	NCDC	21.5786	-158.0414	1000	04/1965 - 12/2005	19	7
51-7194	PAAKEA 350	HI	Maui	NCDC	20.8169	-156.1219	1260	03/1965 - 12/2005	12	2
51-7209	PAAUHAU MAUKA 217.2	HI	Hawaii	NCDC	20.0731	-155.4472	1120	01/1976 - 12/2005	10	1
51-7465	PAHOA SCHOOL SITE 64	HI	Hawaii	NCDC	19.4939	-154.9456	683	01/1979 - 12/2005	2	1
51-7942	PEARL CTRY CLUB 760.2	HI	Oahu	NCDC	21.3933	-157.9328	220	09/1977 - 12/2005	26	7
51-8155	PH WAINIHA 1115	HI	Kauai	NCDC	22.1961	-159.5561	101	02/1966 - 12/2005	14	5
51-8063	POHAKULOA 107	HI	Hawaii	NCDC	19.7528	-155.5294	6511	03/1965 - 12/2005	28	11
51-8165	PRINCEVILLE RANCH 1117	HI	Kauai	NCDC	22.2181	-159.4828	217	03/1965 - 12/2005	8	4
51-8314	PUNALUU PUMP 905.2	HI	Oahu	NCDC	21.5844	-157.8914	20	12/1966 - 12/2005	19	3
51-8342	PUPUKEA HEIGHTS 896.4	HI	Oahu	NCDC	21.6408	-158.0364	750	09/1968 - 12/2005	19	7
51-8555	PUU WAAWAA 94.1	HI	Hawaii	NCDC	19.7811	-155.8458	2520	03/1965 - 12/2005	20	8
51-8549	PUU-O-HOKU RANCH 542.1	HI	Molokai	NCDC	21.1436	-156.7347	700	04/1965 - 12/2005	5	2
51-8760	ULUPALAKUA RANCH 250	HI	Maui	NCDC	20.6519	-156.4008	1900	03/1965 - 12/2005	25	6
51-8941	WAHIAWA 930	HI	Kauai	NCDC	21.8967	-159.5569	215	03/1965 - 12/2005	27	10
51-8945	WAHIAWA DAM 863	HI	Oahu	NCDC	21.4967	-158.0497	854	04/1965 - 12/2005	19	7
51-8966	WAIAHI UPPER 1052	HI	Kauai	NCDC	22.0219	-159.4644	780	06/1987 - 12/2005	14	5

Station ID	Station name	State	Island	Source of data	Latitude	Longitude	Elevation (feet)	Period of record	Daily region	Hourly region
51-8964	WAIAHOLE 837	HI	Oahu	NCDC	21.4705	-157.8836	745	05/1965 - 12/2005	14	5
51-9195	WAIALUA 847	HI	Oahu	NCDC	21.5744	-158.1206	32	03/1965 - 12/2005	22	10
51-9335	WAIKAMOI DAM 336	HI	Maui	NCDC	20.8122	-156.2328	4320	03/1965 - 12/2005	12	5
51-9376	WAIKAPU 390	HI	Maui	NCDC	20.8522	-156.5122	425	07/1979 - 12/2005	21	9
51-9500	WAILUPE VALLEY SCH 723.6	HI	Oahu	NCDC	21.2919	-157.7525	180	04/1966 - 12/2005	26	7
51-9534	WAIMANALO NONOKIO 795.2	HI	Oahu	NCDC	21.3356	-157.7114	120	11/1972 - 12/2005	6	3
51-9593	WAIMEA 892	HI	Oahu	NCDC	21.6261	-158.0678	330	03/1965 - 12/2005	19	7

Table A.6.3. List of supplemental stations (see Section 4.5.3) used in the analysis showing station ID, station name, state, island, source of data, latitude, longitude, elevation, period of record and daily and hourly precipitation frequency region used to group stations for analysis.

Station ID	Station name	State	Island	Source of data	Latitude	Longitude	Elevation (feet)	Period of record	Daily region	Hourly region
56-0164	BIG BOG	HI	Maui	HaleNet	20.7297	-156.0950	5413	01/1993 - 08/2007	18	5
51-6565	MOUNT WAIALEALE 1047	HI	Kauai	NCDC	22.0656	-159.5008	5148	11/1949 - 10/2004	14	5
51-8433	PUU KUKUI 380	HI	Maui	NCDC	20.8950	-156.5897	5790	02/1985 - 12/2005	18	5

Table A.6.4. List of n-minute stations used in the analysis showing station ID, station name, state and island, source of data, latitude, longitude, elevation, and period of record.

Station ID	Station name	State	Island	Source of data	Latitude	Longitude	Elevation (feet)	Period of record
51-1919	HONOLULU INTL AP 703	HI	Oahu	NCDC	21.3219	-157.9253	7	01/1984 - 12/2005
51-2572	KAHULUI WSO AP 398	HI	Maui	NCDC	20.8997	-156.4286	51	01/1984 - 12/2005
51-5580	LIHUE WSO AP 1020.1	HI	Kauai	NCDC	21.9839	-159.3406	100	01/1973 - 12/2005

Appendix A.7. Selected statistical characteristics of daily and hourly regions.

Table A.7.1. Number of stations, total number of data years, and regional L-moment ratios for each daily region and duration.

Daily region	Duration	Number of stations	Number of data years	L-CV	L-skewness	L-kurtosis
1	24-hour	9	585	0.2537	0.2619	0.1813
	48-hour	7	483	0.2649	0.2766	0.1640
	4-day	7	511	0.2673	0.2770	0.1963
	7-day	7	511	0.2638	0.2706	0.2131
	10-day	7	511	0.2508	0.2656	0.2052
	20-day	7	511	0.2430	0.2582	0.2030
	30-day	7	511	0.2416	0.2822	0.2110
	45-day	7	511	0.2350	0.2741	0.2045
	60-day	7	511	0.2244	0.2621	0.2096
2	24-hour	18	846	0.2274	0.2094	0.1798
	48-hour	12	576	0.2242	0.1989	0.1823
	4-day	12	684	0.2304	0.1923	0.1816
	7-day	12	684	0.2247	0.1802	0.1751
	10-day	12	684	0.2140	0.1611	0.1568
	20-day	12	684	0.2002	0.1695	0.1491
	30-day	12	684	0.1883	0.1598	0.1271
	45-day	12	684	0.1838	0.1920	0.1677
	60-day	12	684	0.1795	0.1788	0.1525
3	24-hour	6	246	0.2964	0.3082	0.1887
	48-hour	5	220	0.2835	0.2988	0.2078
	4-day	5	225	0.2776	0.3069	0.1984
	7-day	5	225	0.2642	0.2820	0.2078
	10-day	5	225	0.2473	0.2679	0.1867
	20-day	5	225	0.2262	0.2356	0.1457
	30-day	5	225	0.2207	0.2428	0.1573
	45-day	5	225	0.2048	0.2299	0.1698
	60-day	5	225	0.1896	0.2306	0.1681
4	24-hour	10	410	0.2795	0.2066	0.1362
	48-hour	6	204	0.2892	0.2285	0.1464
	4-day	6	234	0.2977	0.2700	0.1811
	7-day	6	240	0.2933	0.2662	0.1860
	10-day	6	246	0.2799	0.2698	0.1937
	20-day	6	258	0.2729	0.2525	0.1781
	30-day	6	258	0.2713	0.2394	0.1337
	45-day	6	258	0.2566	0.1983	0.1179
	60-day	6	258	0.2533	0.1897	0.1035

Daily region	Duration	Number of stations	Number of data years	L-CV	L-skewness	L-kurtosis
5	24-hour	10	430	0.2645	0.2219	0.1421
	48-hour	6	294	0.2609	0.2176	0.1300
	4-day	6	342	0.2614	0.2122	0.1419
	7-day	6	348	0.2514	0.1782	0.1311
	10-day	6	348	0.2480	0.1670	0.1149
	20-day	6	354	0.2322	0.1815	0.1349
	30-day	7	371	0.2221	0.1695	0.1349
	45-day	7	371	0.2161	0.1520	0.1171
	60-day	7	371	0.2141	0.1644	0.1217
6	24-hour	7	266	0.2602	0.1501	0.1115
	48-hour	4	152	0.2593	0.1166	0.1139
	4-day	5	200	0.2769	0.1576	0.1218
	7-day	5	200	0.2673	0.1502	0.1335
	10-day	5	200	0.2655	0.1312	0.1087
	20-day	5	200	0.2594	0.1605	0.1031
	30-day	5	200	0.2491	0.1587	0.1024
	45-day	5	200	0.2366	0.1316	0.1029
	60-day	5	200	0.2289	0.1426	0.0992
7	24-hour	8	424	0.2686	0.2264	0.1439
	48-hour	4	256	0.2689	0.2339	0.1350
	4-day	4	268	0.2552	0.1857	0.1119
	7-day	4	268	0.2439	0.1691	0.1181
	10-day	4	272	0.2352	0.1530	0.1150
	20-day	4	272	0.2274	0.1699	0.1305
	30-day	4	272	0.2191	0.2030	0.1364
	45-day	4	272	0.2150	0.1951	0.1359
	60-day	4	276	0.2084	0.1928	0.1436
8	24-hour	6	288	0.2935	0.2400	0.2103
	48-hour	4	200	0.3064	0.3012	0.2642
	4-day	5	285	0.2622	0.2615	0.2715
	7-day	5	290	0.2586	0.2492	0.2351
	10-day	5	290	0.2431	0.2351	0.2285
	20-day	5	290	0.2196	0.1804	0.1857
	30-day	5	290	0.2137	0.1960	0.1708
	45-day	5	290	0.2074	0.2014	0.1734
	60-day	5	290	0.1902	0.1895	0.1837
9	24-hour	37	1480	0.2971	0.2380	0.1512
	48-hour	12	528	0.2871	0.2290	0.1391
	4-day	15	960	0.2588	0.1687	0.1354
	7-day	15	960	0.2483	0.1503	0.1399
	10-day	16	976	0.2390	0.1339	0.1334
	20-day	16	976	0.2243	0.1159	0.1423
	30-day	16	976	0.2197	0.1222	0.1438
	45-day	16	976	0.2137	0.1174	0.1256
	60-day	16	976	0.2029	0.1061	0.1220

Daily region	Duration	Number of stations	Number of data years	L-CV	L-skewness	L-kurtosis
10	24-hour	12	492	0.2383	0.2402	0.1797
	48-hour	9	387	0.2509	0.2410	0.1698
	4-day	9	414	0.2573	0.2867	0.2097
	7-day	9	414	0.2539	0.2999	0.2350
	10-day	9	414	0.2426	0.2965	0.2391
	20-day	9	414	0.2295	0.2713	0.1973
	30-day	9	414	0.2181	0.2798	0.2110
	45-day	9	414	0.2158	0.2622	0.2009
	60-day	9	414	0.2080	0.2439	0.1895
11	24-hour	12	492	0.2189	0.1988	0.1701
	48-hour	7	315	0.2067	0.1966	0.1557
	4-day	7	336	0.2152	0.2101	0.1666
	7-day	8	352	0.2127	0.1952	0.1635
	10-day	8	360	0.2033	0.1901	0.1497
	20-day	8	360	0.1973	0.1890	0.1502
	30-day	8	360	0.1853	0.1727	0.1451
	45-day	8	360	0.1789	0.2028	0.1940
	60-day	7	336	0.1734	0.2030	0.1712
12	24-hour	15	585	0.2242	0.1642	0.1125
	48-hour	8	328	0.2347	0.2261	0.1191
	4-day	9	414	0.2221	0.1825	0.1276
	7-day	9	414	0.2188	0.2014	0.1467
	10-day	9	414	0.2144	0.2112	0.1443
	20-day	9	423	0.1924	0.1799	0.1387
	30-day	9	423	0.1809	0.1837	0.1372
	45-day	9	423	0.1732	0.1810	0.1473
	60-day	9	423	0.1651	0.1855	0.1764
13	24-hour	10	330	0.2385	0.1432	0.1129
	48-hour	1	34	0.2338	0.2385	0.1589
	4-day	5	195	0.2065	0.1127	0.1482
	7-day	5	195	0.1954	0.0932	0.1861
	10-day	5	200	0.1955	0.0841	0.1361
	20-day	5	200	0.1817	0.1120	0.1116
	30-day	5	200	0.1798	0.1468	0.1397
	45-day	5	200	0.1718	0.1259	0.1159
	60-day	5	200	0.1650	0.1186	0.1198
14	24-hour	19	817	0.2206	0.2044	0.1416
	48-hour	11	528	0.2144	0.1724	0.1234
	4-day	16	720	0.2098	0.1495	0.1386
	7-day	16	720	0.1976	0.1508	0.1523
	10-day	16	720	0.1918	0.1470	0.1376
	20-day	16	736	0.1724	0.1450	0.1417
	30-day	16	736	0.1625	0.1436	0.1281
	45-day	16	736	0.1567	0.1328	0.1282
	60-day	16	736	0.1437	0.1221	0.1197

Daily region	Duration	Number of stations	Number of data years	L-CV	L-skewness	L-kurtosis
15	24-hour	5	250	0.2658	0.1512	0.1089
	48-hour	2	112	0.2574	0.1857	0.1353
	4-day	2	114	0.2516	0.2240	0.1716
	7-day	2	114	0.2340	0.2120	0.1921
	10-day	2	114	0.2376	0.2313	0.2166
	20-day	2	114	0.2387	0.2521	0.1861
	30-day	2	114	0.2266	0.1919	0.1654
	45-day	2	114	0.2102	0.1451	0.1452
	60-day	2	114	0.1989	0.1306	0.1277
16	24-hour	9	405	0.2917	0.1809	0.1542
	48-hour	8	328	0.3032	0.2155	0.1612
	4-day	9	387	0.2964	0.2096	0.1606
	7-day	9	387	0.2892	0.1994	0.1489
	10-day	9	387	0.2933	0.2027	0.1390
	20-day	9	396	0.2814	0.1988	0.1517
	30-day	9	396	0.2725	0.1871	0.1483
	45-day	9	396	0.2633	0.1507	0.1174
	60-day	9	396	0.2508	0.1210	0.1060
17	24-hour	12	516	0.2359	0.2732	0.1786
	48-hour	10	410	0.2341	0.2545	0.1754
	4-day	11	528	0.2298	0.2354	0.1414
	7-day	11	528	0.2300	0.2433	0.1553
	10-day	11	528	0.2172	0.2115	0.1314
	20-day	11	528	0.1982	0.1962	0.1433
	30-day	11	539	0.1910	0.2001	0.1549
	45-day	11	528	0.1831	0.2073	0.1527
	60-day	11	528	0.1744	0.1864	0.1481
18	24-hour	15	630	0.2471	0.2152	0.1520
	48-hour	6	300	0.2313	0.2081	0.1598
	4-day	8	376	0.2306	0.1889	0.1249
	7-day	8	368	0.2182	0.1554	0.1278
	10-day	9	396	0.2120	0.1442	0.1165
	20-day	9	405	0.2028	0.1255	0.1040
	30-day	9	405	0.1986	0.1225	0.0881
	45-day	9	405	0.2024	0.1307	0.0873
	60-day	9	405	0.1901	0.1293	0.0902
19	24-hour	30	1140	0.3008	0.2004	0.1180
	48-hour	10	400	0.2899	0.2094	0.1010
	4-day	13	559	0.2727	0.1604	0.0957
	7-day	13	572	0.2642	0.1506	0.0979
	10-day	13	572	0.2593	0.1342	0.0867
	20-day	13	572	0.2505	0.1242	0.0818
	30-day	13	572	0.2408	0.1327	0.0930
	45-day	13	572	0.2350	0.1379	0.0831
	60-day	13	572	0.2251	0.1283	0.0769

Daily region	Duration	Number of stations	Number of data years	L-CV	L-skewness	L-kurtosis
20	24-hour	15	510	0.2968	0.2489	0.1676
	48-hour	7	217	0.3204	0.2497	0.1553
	4-day	7	224	0.3112	0.2344	0.1253
	7-day	7	224	0.3089	0.2422	0.1443
	10-day	7	224	0.3049	0.2203	0.1224
	20-day	7	231	0.2971	0.2216	0.1006
	30-day	7	231	0.3068	0.2403	0.1209
	45-day	7	231	0.2956	0.2071	0.0901
	60-day	7	231	0.2894	0.1943	0.0897
21	24-hour	28	1120	0.3027	0.2498	0.2041
	48-hour	14	728	0.3088	0.2515	0.1906
	4-day	15	780	0.3070	0.2422	0.1857
	7-day	16	816	0.3027	0.2037	0.1544
	10-day	16	816	0.2946	0.2002	0.1620
	20-day	16	816	0.2924	0.1949	0.1425
	30-day	16	832	0.2915	0.1956	0.1331
	45-day	16	832	0.2934	0.1847	0.1295
	60-day	16	832	0.2887	0.1789	0.1223
22	24-hour	19	779	0.2897	0.2154	0.1540
	48-hour	12	480	0.3132	0.2346	0.1256
	4-day	13	572	0.3154	0.2218	0.1092
	7-day	13	572	0.3131	0.2257	0.1050
	10-day	13	572	0.3179	0.2333	0.1129
	20-day	13	572	0.3175	0.2370	0.1106
	30-day	13	572	0.3117	0.2159	0.1024
	45-day	13	585	0.3047	0.1928	0.0931
	60-day	13	585	0.2932	0.1795	0.0913
23	24-hour	8	368	0.2031	0.1950	0.1362
	48-hour	7	301	0.2018	0.2110	0.1466
	4-day	7	357	0.1958	0.1616	0.1294
	7-day	7	364	0.1918	0.1876	0.1757
	10-day	7	364	0.1826	0.1916	0.1889
	20-day	7	371	0.1728	0.1783	0.1797
	30-day	7	371	0.1689	0.1380	0.1390
	45-day	7	371	0.1572	0.1135	0.1474
	60-day	7	371	0.1519	0.1218	0.1327
24	24-hour	6	222	0.2737	0.2257	0.1796
	48-hour	4	168	0.2840	0.2628	0.1845
	4-day	6	234	0.2632	0.2353	0.1561
	7-day	6	234	0.2545	0.2391	0.1745
	10-day	6	240	0.2459	0.1893	0.1419
	20-day	6	240	0.2223	0.1832	0.1467
	30-day	6	240	0.2266	0.2005	0.1389
	45-day	6	240	0.2182	0.1528	0.1139
	60-day	6	240	0.2095	0.1375	0.1156

Daily region	Duration	Number of stations	Number of data years	L-CV	L-skewness	L-kurtosis
25	24-hour	28	1176	0.2649	0.1977	0.1497
	48-hour	11	583	0.2627	0.2008	0.1326
	4-day	13	650	0.2683	0.2165	0.1474
	7-day	13	663	0.2689	0.2047	0.1469
	10-day	13	663	0.2620	0.1840	0.1424
	20-day	13	676	0.2534	0.1871	0.1288
	30-day	13	689	0.2489	0.1825	0.1209
	45-day	13	689	0.2426	0.1574	0.1079
	60-day	13	689	0.2373	0.1498	0.1001
26	24-hour	21	924	0.2890	0.2416	0.1733
	48-hour	14	630	0.2954	0.2408	0.1607
	4-day	15	750	0.2865	0.2098	0.1201
	7-day	15	750	0.2823	0.2115	0.1240
	10-day	15	750	0.2790	0.2046	0.1255
	20-day	15	750	0.2676	0.1872	0.0955
	30-day	15	750	0.2572	0.1719	0.0858
	45-day	15	750	0.2604	0.1763	0.0898
	60-day	15	750	0.2435	0.1606	0.0823
27	24-hour	27	1242	0.2516	0.1487	0.1161
	48-hour	11	693	0.2498	0.2039	0.1413
	4-day	13	858	0.2598	0.2081	0.1533
	7-day	13	858	0.2601	0.2046	0.1679
	10-day	13	871	0.2609	0.1943	0.1509
	20-day	13	884	0.2640	0.1895	0.1249
	30-day	13	884	0.2649	0.1919	0.1109
	45-day	13	884	0.2625	0.1786	0.1075
	60-day	13	884	0.2612	0.1788	0.0996
28	24-hour	6	240	0.3235	0.2801	0.1651
	48-hour	5	185	0.3326	0.3154	0.1689
	4-day	5	215	0.3373	0.3241	0.1911
	7-day	5	220	0.3437	0.3271	0.1701
	10-day	5	225	0.3343	0.3136	0.1737
	20-day	5	235	0.3321	0.2558	0.1270
	30-day	5	235	0.3165	0.2365	0.1296
	45-day	5	240	0.3140	0.2278	0.1235
	60-day	5	240	0.3000	0.2145	0.1304

Table A.7.2. Number of stations, total number of data years, and regional L-moment ratios for each hourly region and duration.

Hourly region	Duration	Number of stations	Number of data years	L-CV	L-skewness	L-kurtosis
1	60-minute	6	174	0.1954	0.1357	0.1303
	2-hour	6	180	0.2076	0.1642	0.1695
	3-hour	6	174	0.2082	0.1590	0.1466
	6-hour	6	180	0.2176	0.1664	0.1230
	12-hour	6	180	0.2137	0.1893	0.1553
2	60-minute	9	252	0.2523	0.2327	0.1962
	2-hour	9	252	0.2466	0.2020	0.1729
	3-hour	9	252	0.2444	0.2142	0.1670
	6-hour	9	252	0.2396	0.1924	0.1448
	12-hour	9	261	0.2406	0.1756	0.1137
3	60-minute	6	198	0.2380	0.2038	0.1774
	2-hour	6	198	0.2441	0.1986	0.1840
	3-hour	6	198	0.2454	0.1842	0.1683
	6-hour	6	198	0.2541	0.2190	0.1878
	12-hour	6	198	0.2502	0.2139	0.1906
4	60-minute	5	185	0.2679	0.2232	0.1390
	2-hour	5	185	0.2808	0.2264	0.1781
	3-hour	5	185	0.2925	0.2361	0.1840
	6-hour	5	185	0.3016	0.2468	0.1941
	12-hour	5	185	0.3060	0.2309	0.1860
5	60-minute	10	310	0.2024	0.1676	0.1550
	2-hour	10	310	0.2029	0.1437	0.1337
	3-hour	10	310	0.2000	0.1380	0.1091
	6-hour	10	310	0.2117	0.1234	0.1000
	12-hour	10	310	0.2157	0.1358	0.1066
6	60-minute	5	185	0.2131	0.1859	0.1458
	2-hour	5	185	0.2224	0.1686	0.1561
	3-hour	5	185	0.2252	0.1555	0.1538
	6-hour	5	185	0.2383	0.1689	0.1507
	12-hour	5	185	0.2510	0.1651	0.1416
7	60-minute	9	297	0.2369	0.1761	0.1554
	2-hour	9	297	0.2452	0.1812	0.1622
	3-hour	9	297	0.2484	0.1629	0.1694
	6-hour	9	297	0.2572	0.1432	0.1525
	12-hour	9	297	0.2690	0.1397	0.1319
8	60-minute	8	248	0.2339	0.1813	0.1105
	2-hour	8	248	0.2259	0.1657	0.1231
	3-hour	8	240	0.2319	0.2022	0.1410
	6-hour	8	240	0.2473	0.2581	0.1607
	12-hour	8	240	0.2689	0.2641	0.1651

Hourly region	Duration	Number of stations	Number of data years	L-CV	L-skewness	L-kurtosis
9	60-minute	5	150	0.2700	0.1832	0.1423
	2-hour	5	150	0.2737	0.1751	0.0990
	3-hour	5	155	0.2787	0.1595	0.0952
	6-hour	5	150	0.2945	0.1834	0.1250
	12-hour	5	150	0.3001	0.1662	0.1194
10	60-minute	7	266	0.2267	0.1466	0.1046
	2-hour	7	259	0.2280	0.1558	0.1073
	3-hour	7	259	0.2271	0.1373	0.1080
	6-hour	7	259	0.2427	0.1233	0.0792
	12-hour	7	259	0.2490	0.1328	0.0871
11	60-minute	1	37	0.1736	0.0620	0.0730
	2-hour	1	37	0.2023	0.1388	0.0201
	3-hour	1	38	0.2059	0.1639	0.0451
	6-hour	1	37	0.2007	0.1594	0.1970
	12-hour	1	37	0.2594	0.2272	0.1838

Appendix A.8. Heterogeneity statistic, H1, for daily and hourly regions

Table A.8.1. H1 for daily regions for durations 24-hour through 60-day.

Daily region	Duration								
	24-hr	2-day	4-day	7-day	10-day	20-day	30-day	45-day	60-day
1	-0.96	-1.95	-1.33	-1.64	-1.65	-1.87	-1.74	-1.54	-1.32
2	1.05	-1.44	-1.22	-0.50	0.20	-1.24	-0.16	-0.60	-0.33
3	-1.19	-0.87	-0.31	-0.71	-0.17	0.65	0.23	0.35	-0.19
4	0.60	-0.99	-0.65	-0.68	-0.94	-0.39	0.56	0.11	0.56
5	-0.13	-1.37	-1.90	-0.87	-0.97	0.15	0.55	1.16	1.04
6	0.25	0.42	0.56	0.10	-0.07	-0.23	-0.79	-0.57	-1.10
7	0.96	-1.10	-0.99	-1.69	-1.55	-0.05	0.11	0.80	0.75
8	0.44	-0.16	0.09	0.10	0.74	0.64	0.24	-0.70	-0.56
9	-0.32	0.59	1.50	1.06	0.49	0.03	0.48	0.76	0.94
10	0.35	-0.02	-0.36	-0.43	-0.40	-0.36	0.28	0.85	0.91
11	-0.93	-1.48	-0.78	1.23	1.86	0.95	0.84	0.66	2.20
12	0.92	0.34	2.23	0.57	0.09	-0.40	-0.11	0.16	-0.15
13	-0.40	n/a	2.35	1.16	1.11	0.32	-0.27	-0.48	-1.08
14	0.02	0.65	2.01	2.06	1.86	1.67	1.30	1.56	3.90
15	1.92	-1.14	-0.64	-0.56	-0.65	-0.83	-0.97	-1.33	-1.28
16	1.84	1.43	1.08	1.84	2.30	1.41	0.51	0.70	1.08
17	-0.55	-1.68	-1.25	-1.97	-2.20	-1.66	-0.34	-0.53	0.80
18	0.69	1.56	2.76	2.01	2.17	1.19	2.25	1.09	1.92
19	-0.58	0.39	-0.63	-0.99	-1.08	-0.51	-0.25	-0.09	-0.25
20	-0.06	-0.06	0.72	-0.29	0.03	1.00	2.42	3.10	3.18
21	-1.38	-0.67	-0.51	0.12	0.25	1.98	2.40	3.39	4.25
22	0.44	0.24	0.22	0.28	0.22	-0.46	-0.36	0.51	0.38
23	1.11	0.81	1.44	1.28	0.92	1.08	2.43	2.97	2.93
24	1.20	1.09	1.14	0.56	1.16	0.26	1.07	1.61	1.43
25	-0.43	0.49	-0.35	-0.42	0.90	0.63	2.16	2.57	3.40
26	-0.15	-1.18	-1.11	-0.63	0.12	0.14	-0.10	-0.03	0.64
27	-0.88	1.76	0.49	0.82	1.58	3.36	3.85	4.22	4.64
28	-1.35	-0.23	-0.97	-1.01	-0.85	0.15	0.94	0.82	0.44

Table A.8.2. H1 for hourly regions for durations 60-minute through 12-hour.
(Note that region 11 only had one station, so H1 was not calculated.)

Hourly region	Duration				
	60-min	2-hour	3-hour	6-hour	12-hour
1	-0.79	0.15	-0.08	-0.67	-0.64
2	-0.18	1.32	1.86	2.07	2.29
3	0.11	-1.29	-0.75	-0.88	-0.87
4	1.64	1.73	1.05	0.91	1.76
5	-0.76	1.00	1.49	-0.74	-0.50
6	0.50	-0.14	0.06	0.26	-0.36
7	0.60	0.12	0.00	0.34	0.16
8	0.36	0.00	-0.89	-1.24	-0.91
9	0.48	-0.40	-1.15	-1.06	-1.50
10	-0.47	-0.39	-1.12	-0.04	-0.38
11	n/a	n/a	n/a	n/a	n/a

Appendix A.9. Regional growth factors for daily and hourly regions

Table A.9.1. Regional growth factors (RGF) for daily regions for selected durations from 24-hour to 60-day based on the annual maximum series results. RGFs for the annual exceedance probability (AEP) of 63.29% were computed to assist in calculation of 1-year average recurrence interval (ARI) magnitudes for partial duration series results (see Section 4.5.4).

Daily region	Duration	RGFs for selected AEP (%)									
		63.29	**50.00**	**20.00**	**10.00**	**4.00**	**2.00**	**1.00**	**0.50**	**0.20**	**0.10**
1	24-hour	0.768	0.887	1.295	1.603	2.041	2.405	2.803	3.240	3.885	4.429
	48-hour	0.754	0.876	1.300	1.627	2.099	2.498	2.942	3.435	4.176	4.813
	4-day	0.752	0.875	1.303	1.632	2.109	2.513	2.961	3.460	4.210	4.855
	7-day	0.757	0.879	1.302	1.625	2.089	2.479	2.909	3.385	4.095	4.700
	10-day	0.770	0.886	1.290	1.596	2.032	2.397	2.797	3.237	3.890	4.444
	20-day	0.778	0.893	1.285	1.579	1.994	2.339	2.714	3.123	3.725	4.232
	30-day	0.775	0.885	1.271	1.570	2.006	2.377	2.792	3.255	3.957	4.563
	45-day	0.783	0.891	1.268	1.556	1.973	2.324	2.713	3.145	3.791	4.345
	60-day	0.794	0.900	1.261	1.534	1.921	2.243	2.596	2.983	3.554	4.036
2	24-hour	0.802	0.917	1.287	1.547	1.893	2.163	2.442	2.732	3.134	3.453
	48-hour	0.807	0.921	1.288	1.540	1.872	2.128	2.389	2.658	3.026	3.314
	4-day	0.803	0.922	1.298	1.556	1.891	2.146	2.407	2.672	3.032	3.312
	7-day	0.811	0.928	1.295	1.542	1.859	2.096	2.335	2.575	2.896	3.142
	10-day	0.824	0.938	1.288	1.516	1.802	2.011	2.217	2.421	2.686	2.884
	20-day	0.833	0.939	1.267	1.483	1.757	1.960	2.161	2.361	2.626	2.826
	30-day	0.845	0.946	1.254	1.455	1.705	1.888	2.068	2.245	2.476	2.649
	45-day	0.843	0.938	1.238	1.443	1.710	1.914	2.121	2.332	2.619	2.841
	60-day	0.849	0.943	1.236	1.433	1.685	1.874	2.063	2.253	2.507	2.701
3	24-hour	0.718	0.848	1.316	1.691	2.255	2.750	3.317	3.969	4.983	5.887
	48-hour	0.732	0.858	1.308	1.664	2.193	2.653	3.175	3.768	4.683	5.488
	4-day	0.736	0.858	1.297	1.648	2.175	2.637	3.165	3.771	4.714	5.552
	7-day	0.754	0.874	1.296	1.623	2.100	2.506	2.958	3.465	4.231	4.893
	10-day	0.772	0.887	1.285	1.587	2.019	2.381	2.780	3.220	3.873	4.429
	20-day	0.798	0.908	1.275	1.542	1.909	2.205	2.519	2.855	3.336	3.729
	30-day	0.801	0.908	1.265	1.528	1.892	2.188	2.505	2.847	3.339	3.746
	45-day	0.818	0.918	1.251	1.491	1.819	2.081	2.359	2.653	3.072	3.412
	60-day	0.831	0.924	1.232	1.455	1.759	2.002	2.260	2.534	2.923	3.240
4	24-hour	0.757	0.899	1.355	1.673	2.095	2.423	2.761	3.112	3.596	3.979
	48-hour	0.743	0.885	1.355	1.694	2.155	2.524	2.913	3.325	3.911	4.386
	4-day	0.725	0.863	1.342	1.706	2.229	2.668	3.152	3.688	4.485	5.165
	7-day	0.730	0.867	1.339	1.696	2.207	2.634	3.104	3.620	4.387	5.038
	10-day	0.742	0.872	1.321	1.664	2.156	2.568	3.023	3.526	4.274	4.913
	20-day	0.752	0.882	1.323	1.651	2.112	2.490	2.901	3.347	3.997	4.540
	30-day	0.757	0.888	1.328	1.649	2.094	2.453	2.837	3.249	3.841	4.327
	45-day	0.779	0.910	1.329	1.618	1.998	2.289	2.588	2.894	3.313	3.641
	60-day	0.784	0.915	1.329	1.611	1.977	2.255	2.538	2.825	3.214	3.515

Daily region	Duration	RGFs for selected AEP (%)									
		63.29	50.00	20.00	10.00	4.00	2.00	1.00	0.50	0.20	0.10
5	24-hour	0.767	0.898	1.328	1.635	2.051	2.379	2.724	3.088	3.599	4.010
	48-hour	0.771	0.901	1.326	1.627	2.033	2.352	2.685	3.035	3.524	3.915
	4-day	0.772	0.903	1.329	1.629	2.029	2.343	2.668	3.007	3.479	3.854
	7-day	0.789	0.920	1.331	1.607	1.959	2.222	2.487	2.752	3.106	3.377
	10-day	0.794	0.926	1.331	1.599	1.935	2.184	2.430	2.675	2.996	3.238
	20-day	0.804	0.925	1.305	1.560	1.888	2.135	2.384	2.634	2.969	3.226
	30-day	0.815	0.933	1.296	1.536	1.840	2.065	2.288	2.510	2.803	3.025
	45-day	0.824	0.941	1.294	1.521	1.802	2.006	2.204	2.397	2.647	2.831
	60-day	0.823	0.937	1.287	1.517	1.805	2.017	2.227	2.434	2.706	2.910
6	24-hour	0.789	0.929	1.354	1.628	1.964	2.207	2.444	2.674	2.970	3.189
	48-hour	0.799	0.944	1.366	1.623	1.926	2.135	2.331	2.515	2.742	2.902
	4-day	0.773	0.921	1.374	1.668	2.034	2.301	2.563	2.820	3.154	3.402
	7-day	0.783	0.927	1.364	1.645	1.991	2.241	2.483	2.720	3.025	3.249
	10-day	0.790	0.936	1.369	1.640	1.964	2.193	2.410	2.618	2.879	3.066
	20-day	0.787	0.925	1.349	1.626	1.971	2.224	2.473	2.718	3.038	3.277
	30-day	0.796	0.929	1.336	1.601	1.931	2.173	2.409	2.642	2.945	3.171
	45-day	0.813	0.943	1.329	1.570	1.859	2.063	2.258	2.443	2.677	2.844
	60-day	0.816	0.941	1.314	1.552	1.841	2.048	2.248	2.441	2.687	2.866
7	24-hour	0.762	0.894	1.331	1.645	2.071	2.410	2.768	3.147	3.682	4.116
	48-hour	0.760	0.891	1.328	1.645	2.079	2.429	2.800	3.195	3.760	4.222
	4-day	0.784	0.916	1.333	1.616	1.980	2.256	2.535	2.817	3.197	3.490
	7-day	0.797	0.926	1.325	1.589	1.921	2.168	2.413	2.656	2.977	3.219
	10-day	0.808	0.935	1.319	1.568	1.874	2.097	2.314	2.526	2.800	3.002
	20-day	0.811	0.931	1.303	1.549	1.860	2.090	2.319	2.548	2.848	3.076
	30-day	0.811	0.922	1.279	1.528	1.856	2.109	2.370	2.639	3.009	3.301
	45-day	0.816	0.926	1.277	1.518	1.833	2.075	2.321	2.572	2.915	3.183
	60-day	0.822	0.929	1.270	1.503	1.806	2.038	2.274	2.515	2.842	3.097
8	24-hour	0.736	0.878	1.354	1.703	2.184	2.574	2.991	3.438	4.081	4.610
	48-hour	0.710	0.846	1.331	1.717	2.292	2.792	3.362	4.012	5.015	5.902
	4-day	0.760	0.883	1.305	1.624	2.076	2.452	2.862	3.313	3.977	4.538
	7-day	0.766	0.889	1.307	1.617	2.051	2.406	2.789	3.204	3.807	4.308
	10-day	0.783	0.901	1.296	1.583	1.977	2.294	2.632	2.992	3.507	3.928
	20-day	0.815	0.930	1.289	1.530	1.839	2.072	2.305	2.540	2.854	3.095
	30-day	0.817	0.926	1.275	1.515	1.829	2.070	2.315	2.567	2.910	3.178
	45-day	0.821	0.926	1.265	1.500	1.809	2.047	2.292	2.544	2.890	3.162
	60-day	0.838	0.936	1.247	1.459	1.733	1.942	2.154	2.369	2.661	2.886
9	24-hour	0.734	0.878	1.360	1.711	2.196	2.588	3.006	3.454	4.096	4.623
	48-hour	0.745	0.886	1.353	1.689	2.147	2.514	2.901	3.312	3.895	4.368
	4-day	0.785	0.922	1.345	1.625	1.978	2.239	2.498	2.755	3.095	3.351
	7-day	0.798	0.933	1.338	1.599	1.920	2.152	2.378	2.598	2.881	3.090
	10-day	0.810	0.942	1.331	1.576	1.870	2.078	2.277	2.467	2.707	2.880
	20-day	0.827	0.952	1.317	1.539	1.800	1.981	2.150	2.308	2.503	2.640
	30-day	0.829	0.951	1.308	1.528	1.789	1.971	2.143	2.304	2.505	2.648
	45-day	0.834	0.954	1.301	1.514	1.764	1.937	2.099	2.251	2.439	2.572
	60-day	0.845	0.960	1.289	1.487	1.716	1.872	2.017	2.151	2.314	2.427

Daily region	Duration	RGFs for selected AEP (%)									
		63.29	50.00	20.00	10.00	4.00	2.00	1.00	0.50	0.20	0.10
10	24-hour	0.786	0.901	1.288	1.570	1.961	2.278	2.617	2.981	3.504	3.934
	48-hour	0.775	0.896	1.302	1.600	2.013	2.347	2.705	3.089	3.642	4.098
	4-day	0.759	0.876	1.286	1.606	2.075	2.476	2.926	3.432	4.200	4.868
	7-day	0.760	0.873	1.275	1.594	2.070	2.483	2.952	3.487	4.312	5.040
	10-day	0.771	0.879	1.265	1.569	2.020	2.410	2.853	3.355	4.126	4.804
	20-day	0.788	0.894	1.263	1.544	1.948	2.288	2.663	3.079	3.699	4.228
	30-day	0.797	0.897	1.246	1.515	1.907	2.239	2.609	3.022	3.645	4.182
	45-day	0.802	0.903	1.251	1.513	1.886	2.196	2.535	2.907	3.456	3.920
	60-day	0.813	0.913	1.249	1.497	1.841	2.121	2.422	2.746	3.214	3.600
11	24-hour	0.812	0.923	1.281	1.528	1.851	2.101	2.356	2.618	2.977	3.258
	48-hour	0.823	0.928	1.266	1.498	1.802	2.035	2.274	2.518	2.852	3.112
	4-day	0.812	0.921	1.272	1.518	1.846	2.102	2.367	2.643	3.026	3.330
	7-day	0.818	0.927	1.274	1.513	1.825	2.063	2.307	2.556	2.895	3.160
	10-day	0.827	0.932	1.264	1.490	1.784	2.008	2.235	2.466	2.778	3.020
	20-day	0.832	0.934	1.256	1.476	1.760	1.976	2.195	2.418	2.719	2.952
	30-day	0.845	0.943	1.246	1.447	1.703	1.893	2.082	2.272	2.522	2.712
	45-day	0.845	0.936	1.228	1.431	1.698	1.905	2.118	2.338	2.640	2.877
	60-day	0.850	0.938	1.221	1.418	1.677	1.878	2.084	2.297	2.590	2.821
12	24-hour	0.815	0.934	1.301	1.541	1.843	2.065	2.284	2.502	2.786	2.999
	48-hour	0.792	0.908	1.290	1.563	1.936	2.232	2.544	2.875	3.341	3.719
	4-day	0.812	0.928	1.291	1.536	1.851	2.088	2.326	2.567	2.890	3.138
	7-day	0.811	0.922	1.280	1.527	1.853	2.105	2.363	2.630	2.995	3.282
	10-day	0.813	0.921	1.270	1.516	1.844	2.100	2.365	2.642	3.026	3.331
	20-day	0.838	0.938	1.253	1.464	1.735	1.938	2.142	2.348	2.622	2.832
	30-day	0.847	0.941	1.237	1.437	1.694	1.888	2.083	2.281	2.546	2.751
	45-day	0.854	0.944	1.228	1.418	1.663	1.847	2.031	2.218	2.467	2.658
	60-day	0.860	0.946	1.216	1.398	1.634	1.812	1.992	2.175	2.420	2.610
13	24-hour	0.808	0.938	1.327	1.575	1.877	2.094	2.302	2.504	2.761	2.949
	48-hour	0.790	0.904	1.283	1.560	1.942	2.251	2.580	2.934	3.440	3.857
	4-day	0.841	0.957	1.292	1.496	1.734	1.898	2.051	2.194	2.369	2.491
	7-day	0.854	0.966	1.281	1.467	1.679	1.821	1.950	2.068	2.209	2.306
	10-day	0.856	0.969	1.284	1.467	1.672	1.808	1.931	2.041	2.172	2.261
	20-day	0.860	0.962	1.257	1.436	1.645	1.789	1.923	2.048	2.201	2.309
	30-day	0.855	0.952	1.246	1.434	1.664	1.830	1.990	2.146	2.345	2.492
	45-day	0.865	0.960	1.240	1.414	1.620	1.765	1.901	2.031	2.193	2.308
	60-day	0.872	0.964	1.232	1.397	1.591	1.725	1.851	1.970	2.117	2.220
14	24-hour	0.809	0.921	1.281	1.531	1.862	2.119	2.383	2.656	3.033	3.329
	48-hour	0.821	0.934	1.284	1.517	1.813	2.033	2.251	2.470	2.759	2.978
	4-day	0.830	0.943	1.286	1.506	1.777	1.972	2.162	2.347	2.584	2.759
	7-day	0.840	0.946	1.269	1.477	1.733	1.918	2.098	2.273	2.500	2.667
	10-day	0.845	0.949	1.262	1.463	1.708	1.885	2.056	2.222	2.435	2.592
	20-day	0.861	0.955	1.236	1.416	1.635	1.793	1.945	2.093	2.282	2.420
	30-day	0.869	0.958	1.223	1.392	1.598	1.746	1.888	2.026	2.202	2.330
	45-day	0.876	0.962	1.218	1.378	1.570	1.706	1.836	1.959	2.115	2.228
	60-day	0.888	0.968	1.202	1.346	1.517	1.635	1.747	1.853	1.985	2.078

Daily region	Duration	RGFs for selected AEP (%)									
		63.29	**50.00**	**20.00**	**10.00**	**4.00**	**2.00**	**1.00**	**0.50**	**0.20**	**0.10**
15	24-hour	0.784	0.927	1.362	1.641	1.986	2.235	2.478	2.715	3.020	3.245
	48-hour	0.782	0.915	1.336	1.621	1.989	2.267	2.548	2.833	3.216	3.511
	4-day	0.778	0.902	1.311	1.604	2.001	2.317	2.648	2.998	3.491	3.889
	7-day	0.796	0.913	1.295	1.563	1.921	2.201	2.492	2.795	3.217	3.552
	10-day	0.788	0.905	1.291	1.570	1.951	2.257	2.581	2.925	3.415	3.815
	20-day	0.783	0.897	1.282	1.569	1.972	2.303	2.662	3.051	3.618	4.092
	30-day	0.806	0.923	1.293	1.546	1.876	2.127	2.382	2.642	2.995	3.269
	45-day	0.831	0.945	1.288	1.507	1.775	1.967	2.153	2.333	2.563	2.732
	60-day	0.843	0.953	1.277	1.479	1.722	1.892	2.055	2.210	2.404	2.544
16	24-hour	0.754	0.906	1.383	1.704	2.115	2.425	2.736	3.050	3.469	3.790
	48-hour	0.734	0.886	1.380	1.729	2.197	2.565	2.949	3.350	3.910	4.357
	4-day	0.742	0.891	1.375	1.714	2.165	2.516	2.881	3.260	3.785	4.201
	7-day	0.751	0.898	1.371	1.697	2.125	2.455	2.794	3.141	3.617	3.990
	10-day	0.746	0.895	1.374	1.707	2.145	2.484	2.833	3.193	3.687	4.077
	20-day	0.758	0.901	1.361	1.678	2.095	2.415	2.743	3.080	3.541	3.903
	30-day	0.769	0.910	1.355	1.657	2.048	2.345	2.644	2.948	3.358	3.675
	45-day	0.786	0.928	1.358	1.635	1.976	2.223	2.462	2.696	2.997	3.219
	60-day	0.805	0.944	1.352	1.603	1.900	2.107	2.301	2.484	2.712	2.873
17	24-hour	0.782	0.891	1.269	1.559	1.976	2.328	2.717	3.149	3.794	4.346
	48-hour	0.787	0.898	1.276	1.558	1.955	2.283	2.638	3.025	3.591	4.065
	4-day	0.795	0.906	1.279	1.551	1.923	2.224	2.543	2.884	3.372	3.771
	7-day	0.793	0.904	1.276	1.550	1.930	2.239	2.571	2.928	3.443	3.868
	10-day	0.810	0.920	1.274	1.523	1.855	2.115	2.384	2.665	3.055	3.365
	20-day	0.830	0.931	1.255	1.478	1.769	1.992	2.221	2.454	2.773	3.022
	30-day	0.835	0.933	1.245	1.460	1.744	1.962	2.187	2.417	2.733	2.981
	45-day	0.841	0.933	1.232	1.441	1.718	1.933	2.156	2.387	2.706	2.959
	60-day	0.852	0.942	1.227	1.421	1.670	1.860	2.051	2.245	2.506	2.707
18	24-hour	0.784	0.907	1.310	1.594	1.976	2.275	2.588	2.914	3.369	3.733
	48-hour	0.799	0.916	1.293	1.557	1.908	2.181	2.463	2.756	3.161	3.482
	4-day	0.804	0.923	1.300	1.556	1.889	2.141	2.397	2.657	3.009	3.281
	7-day	0.822	0.939	1.295	1.527	1.813	2.021	2.225	2.425	2.684	2.876
	10-day	0.829	0.945	1.291	1.511	1.781	1.974	2.160	2.341	2.572	2.740
	20-day	0.841	0.953	1.284	1.488	1.732	1.902	2.063	2.216	2.407	2.543
	30-day	0.845	0.955	1.279	1.478	1.714	1.879	2.034	2.180	2.362	2.492
	45-day	0.840	0.952	1.281	1.487	1.734	1.908	2.073	2.231	2.429	2.571
	60-day	0.850	0.955	1.265	1.458	1.689	1.851	2.005	2.152	2.336	2.468
19	24-hour	0.741	0.894	1.385	1.725	2.172	2.516	2.870	3.234	3.732	4.124
	48-hour	0.748	0.894	1.366	1.698	2.139	2.482	2.838	3.208	3.721	4.128
	4-day	0.776	0.921	1.367	1.658	2.021	2.287	2.549	2.806	3.142	3.393
	7-day	0.785	0.928	1.360	1.637	1.979	2.227	2.467	2.702	3.004	3.227
	10-day	0.794	0.937	1.359	1.625	1.944	2.170	2.386	2.593	2.854	3.042
	20-day	0.804	0.943	1.351	1.603	1.902	2.111	2.309	2.496	2.729	2.895
	30-day	0.809	0.942	1.334	1.580	1.876	2.084	2.283	2.474	2.713	2.885
	45-day	0.812	0.941	1.324	1.566	1.859	2.068	2.268	2.460	2.703	2.880
	60-day	0.823	0.947	1.314	1.542	1.814	2.006	2.187	2.360	2.576	2.731

Daily region	Duration	RGFs for selected AEP (%)									
		63.29	**50.00**	**20.00**	**10.00**	**4.00**	**2.00**	**1.00**	**0.50**	**0.20**	**0.10**
20	24-hour	0.731	0.873	1.353	1.709	2.206	2.613	3.052	3.528	4.219	4.793
	48-hour	0.710	0.863	1.381	1.765	2.302	2.743	3.219	3.735	4.485	5.109
	4-day	0.722	0.874	1.379	1.746	2.249	2.654	3.085	3.544	4.200	4.736
	7-day	0.722	0.871	1.372	1.739	2.248	2.662	3.105	3.581	4.268	4.835
	10-day	0.731	0.883	1.379	1.733	2.209	2.586	2.981	3.396	3.978	4.446
	20-day	0.738	0.885	1.369	1.714	2.180	2.548	2.935	3.342	3.915	4.376
	30-day	0.724	0.873	1.370	1.734	2.238	2.645	3.082	3.550	4.223	4.778
	45-day	0.743	0.893	1.375	1.712	2.159	2.506	2.865	3.237	3.751	4.158
	60-day	0.752	0.901	1.373	1.698	2.121	2.445	2.775	3.112	3.571	3.929
21	24-hour	0.726	0.870	1.360	1.722	2.230	2.647	3.097	3.584	4.293	4.883
	48-hour	0.720	0.867	1.366	1.737	2.257	2.684	3.147	3.649	4.380	4.990
	4-day	0.724	0.872	1.369	1.734	2.240	2.651	3.092	3.565	4.247	4.810
	7-day	0.738	0.892	1.386	1.729	2.183	2.534	2.896	3.269	3.783	4.188
	10-day	0.746	0.896	1.377	1.710	2.147	2.485	2.831	3.187	3.674	4.057
	20-day	0.749	0.899	1.377	1.705	2.133	2.461	2.795	3.138	3.603	3.966
	30-day	0.750	0.899	1.376	1.703	2.131	2.458	2.793	3.135	3.602	3.966
	45-day	0.752	0.904	1.383	1.708	2.126	2.442	2.760	3.083	3.516	3.850
	60-day	0.757	0.908	1.380	1.697	2.102	2.405	2.710	3.016	3.425	3.737
22	24-hour	0.746	0.891	1.363	1.697	2.144	2.496	2.862	3.245	3.780	4.207
	48-hour	0.720	0.873	1.381	1.751	2.258	2.666	3.099	3.562	4.223	4.764
	4-day	0.722	0.878	1.392	1.758	2.253	2.645	3.056	3.489	4.098	4.589
	7-day	0.723	0.877	1.386	1.752	2.248	2.642	3.058	3.498	4.119	4.622
	10-day	0.716	0.871	1.388	1.762	2.275	2.687	3.125	3.591	4.256	4.799
	20-day	0.716	0.870	1.385	1.760	2.278	2.695	3.140	3.615	4.297	4.856
	30-day	0.727	0.882	1.390	1.750	2.231	2.610	3.005	3.418	3.995	4.457
	45-day	0.739	0.896	1.394	1.735	2.179	2.518	2.862	3.215	3.693	4.064
	60-day	0.753	0.906	1.386	1.708	2.119	2.429	2.739	3.051	3.468	3.787
23	24-hour	0.826	0.930	1.262	1.490	1.787	2.015	2.247	2.485	2.809	3.062
	48-hour	0.824	0.925	1.254	1.486	1.794	2.035	2.284	2.544	2.905	3.192
	4-day	0.839	0.943	1.263	1.472	1.734	1.926	2.115	2.301	2.545	2.727
	7-day	0.837	0.936	1.250	1.463	1.738	1.947	2.158	2.373	2.663	2.886
	10-day	0.844	0.938	1.236	1.440	1.705	1.908	2.113	2.322	2.606	2.827
	20-day	0.855	0.945	1.228	1.417	1.659	1.840	2.022	2.205	2.448	2.634
	30-day	0.865	0.958	1.233	1.407	1.618	1.768	1.911	2.049	2.224	2.351
	45-day	0.879	0.967	1.222	1.378	1.559	1.685	1.801	1.911	2.045	2.139
	60-day	0.882	0.966	1.213	1.365	1.546	1.671	1.789	1.901	2.039	2.138
24	24-hour	0.758	0.893	1.338	1.657	2.091	2.436	2.799	3.184	3.727	4.166
	48-hour	0.740	0.873	1.330	1.675	2.166	2.575	3.022	3.513	4.239	4.852
	4-day	0.765	0.893	1.320	1.631	2.058	2.401	2.767	3.158	3.716	4.173
	7-day	0.772	0.895	1.308	1.609	2.026	2.363	2.722	3.108	3.662	4.118
	10-day	0.791	0.918	1.319	1.593	1.948	2.217	2.491	2.769	3.145	3.436
	20-day	0.812	0.928	1.291	1.536	1.852	2.090	2.330	2.572	2.897	3.147
	30-day	0.805	0.920	1.290	1.546	1.883	2.142	2.409	2.683	3.059	3.354
	45-day	0.822	0.940	1.296	1.526	1.811	2.017	2.218	2.414	2.668	2.855
	60-day	0.833	0.948	1.289	1.505	1.766	1.951	2.129	2.299	2.515	2.672

Daily region	Duration	RGFs for selected AEP (%)									
		63.29	**50.00**	**20.00**	**10.00**	**4.00**	**2.00**	**1.00**	**0.50**	**0.20**	**0.10**
25	24-hour	0.772	0.908	1.340	1.639	2.029	2.329	2.637	2.952	3.382	3.719
	48-hour	0.773	0.907	1.336	1.633	2.024	2.325	2.634	2.953	3.389	3.732
	4-day	0.765	0.899	1.336	1.645	2.061	2.388	2.729	3.086	3.585	3.984
	7-day	0.767	0.903	1.342	1.648	2.052	2.365	2.688	3.021	3.481	3.844
	10-day	0.778	0.914	1.343	1.632	2.005	2.286	2.570	2.857	3.242	3.539
	20-day	0.785	0.916	1.330	1.611	1.975	2.250	2.529	2.811	3.192	3.487
	30-day	0.790	0.919	1.326	1.601	1.953	2.219	2.486	2.756	3.118	3.396
	45-day	0.801	0.931	1.328	1.585	1.906	2.139	2.368	2.593	2.885	3.103
	60-day	0.808	0.936	1.323	1.572	1.879	2.100	2.315	2.525	2.795	2.993
26	24-hour	0.740	0.880	1.348	1.691	2.167	2.553	2.967	3.411	4.051	4.578
	48-hour	0.735	0.877	1.356	1.707	2.192	2.586	3.007	3.459	4.110	4.646
	4-day	0.750	0.895	1.362	1.690	2.126	2.466	2.819	3.186	3.694	4.097
	7-day	0.754	0.895	1.356	1.679	2.111	2.449	2.799	3.164	3.670	4.073
	10-day	0.758	0.900	1.355	1.672	2.091	2.416	2.751	3.097	3.574	3.950
	20-day	0.773	0.911	1.349	1.646	2.029	2.321	2.615	2.914	3.317	3.628
	30-day	0.785	0.921	1.342	1.621	1.975	2.238	2.499	2.761	3.106	3.368
	45-day	0.782	0.918	1.344	1.628	1.991	2.262	2.533	2.805	3.167	3.442
	60-day	0.800	0.930	1.328	1.588	1.912	2.150	2.383	2.614	2.914	3.138
27	24-hour	0.796	0.932	1.343	1.607	1.931	2.164	2.391	2.612	2.895	3.103
	48-hour	0.784	0.910	1.318	1.602	1.976	2.267	2.565	2.874	3.299	3.633
	4-day	0.774	0.905	1.329	1.626	2.019	2.326	2.643	2.972	3.427	3.788
	7-day	0.775	0.906	1.331	1.627	2.017	2.320	2.632	2.955	3.399	3.750
	10-day	0.777	0.910	1.337	1.629	2.011	2.303	2.600	2.904	3.318	3.641
	20-day	0.775	0.911	1.343	1.637	2.018	2.308	2.602	2.901	3.305	3.619
	30-day	0.774	0.910	1.343	1.639	2.024	2.317	2.616	2.920	3.333	3.654
	45-day	0.779	0.917	1.346	1.633	2.001	2.277	2.554	2.832	3.203	3.486
	60-day	0.780	0.917	1.344	1.630	1.997	2.271	2.547	2.824	3.193	3.476
28	24-hour	0.699	0.847	1.364	1.764	2.345	2.839	3.389	4.003	4.929	5.728
	48-hour	0.682	0.826	1.349	1.772	2.414	2.983	3.638	4.397	5.587	6.656
	4-day	0.676	0.819	1.347	1.779	2.441	3.033	3.722	4.525	5.799	6.953
	7-day	0.669	0.815	1.351	1.792	2.471	3.079	3.789	4.620	5.942	7.143
	10-day	0.681	0.826	1.352	1.777	2.420	2.988	3.642	4.397	5.580	6.640
	20-day	0.697	0.854	1.390	1.791	2.356	2.823	3.330	3.883	4.692	5.371
	30-day	0.717	0.871	1.384	1.758	2.273	2.688	3.130	3.603	4.280	4.834
	45-day	0.721	0.876	1.386	1.754	2.254	2.652	3.074	3.520	4.152	4.665
	60-day	0.737	0.887	1.376	1.722	2.184	2.547	2.924	3.319	3.869	4.309

Table A.9.2. Regional growth factors (RGF) for hourly regions for selected durations from 60-minute to 12-hour based on the annual maximum series results. Note: RGFs for the annual exceedance probability (AEP) of 63.29% were computed to assist in calculation of 1-year average recurrence interval (ARI) magnitudes for partial duration series results (see Section 4.5.4).

Hourly region	**Duration**	**RGFs for selected AEP (%)**									
		63.29	**50.00**	**20.00**	**10.00**	**4.00**	**2.00**	**1.00**	**0.50**	**0.20**	**0.10**
1	60-minute	0.844	0.952	1.270	1.471	1.713	1.885	2.049	2.206	2.405	2.549
	2-hour	0.828	0.939	1.278	1.501	1.781	1.987	2.190	2.391	2.654	2.852
	3-hour	0.829	0.940	1.281	1.502	1.779	1.981	2.179	2.374	2.628	2.817
	6-hour	0.820	0.935	1.291	1.525	1.820	2.038	2.253	2.467	2.747	2.958
	12-hour	0.818	0.928	1.278	1.516	1.824	2.058	2.296	2.538	2.865	3.118
2	60-minute	0.775	0.898	1.308	1.605	2.012	2.338	2.684	3.053	3.578	4.007
	2-hour	0.787	0.912	1.315	1.594	1.962	2.246	2.539	2.840	3.253	3.578
	3-hour	0.786	0.908	1.307	1.588	1.964	2.259	2.567	2.888	3.335	3.692
	6-hour	0.795	0.918	1.310	1.578	1.927	2.193	2.463	2.740	3.115	3.406
	12-hour	0.798	0.925	1.318	1.581	1.915	2.165	2.414	2.665	2.997	3.250
3	60-minute	0.794	0.915	1.303	1.573	1.930	2.206	2.491	2.785	3.189	3.508
	2-hour	0.790	0.915	1.313	1.588	1.949	2.227	2.511	2.803	3.203	3.515
	3-hour	0.792	0.920	1.321	1.592	1.941	2.205	2.471	2.740	3.101	3.379
	6-hour	0.777	0.903	1.317	1.611	2.007	2.319	2.646	2.989	3.470	3.857
	12-hour	0.781	0.906	1.314	1.602	1.987	2.289	2.603	2.930	3.387	3.752
4	60-minute	0.763	0.896	1.332	1.643	2.065	2.400	2.752	3.122	3.645	4.066
	2-hour	0.751	0.889	1.346	1.674	2.120	2.475	2.849	3.245	3.804	4.258
	3-hour	0.738	0.881	1.355	1.701	2.176	2.559	2.967	3.403	4.027	4.538
	6-hour	0.727	0.872	1.360	1.721	2.223	2.634	3.076	3.553	4.245	4.819
	12-hour	0.728	0.877	1.375	1.734	2.225	2.618	3.035	3.477	4.107	4.620
5	60-minute	0.832	0.939	1.270	1.489	1.764	1.967	2.168	2.369	2.632	2.830
	2-hour	0.837	0.947	1.278	1.489	1.747	1.931	2.109	2.281	2.501	2.662
	3-hour	0.840	0.950	1.276	1.482	1.731	1.909	2.079	2.243	2.450	2.601
	6-hour	0.834	0.952	1.297	1.509	1.762	1.938	2.104	2.261	2.457	2.596
	12-hour	0.828	0.947	1.298	1.520	1.787	1.976	2.157	2.331	2.551	2.710
6	60-minute	0.819	0.930	1.278	1.514	1.819	2.049	2.282	2.518	2.836	3.081
	2-hour	0.815	0.933	1.297	1.537	1.840	2.064	2.287	2.508	2.799	3.019
	3-hour	0.816	0.937	1.305	1.543	1.839	2.054	2.265	2.471	2.738	2.937
	6-hour	0.802	0.928	1.318	1.575	1.900	2.141	2.380	2.617	2.931	3.167
	12-hour	0.792	0.926	1.336	1.606	1.944	2.194	2.441	2.685	3.005	3.246
7	60-minute	0.801	0.926	1.313	1.572	1.902	2.148	2.394	2.642	2.970	3.221
	2-hour	0.793	0.921	1.322	1.592	1.938	2.198	2.460	2.724	3.077	3.348
	3-hour	0.795	0.927	1.333	1.599	1.933	2.177	2.419	2.657	2.969	3.203
	6-hour	0.793	0.933	1.353	1.620	1.946	2.179	2.404	2.622	2.899	3.102
	12-hour	0.785	0.932	1.371	1.648	1.986	2.226	2.457	2.679	2.962	3.167
8	60-minute	0.803	0.925	1.307	1.565	1.895	2.143	2.393	2.645	2.983	3.241
	2-hour	0.813	0.933	1.302	1.545	1.850	2.076	2.298	2.519	2.808	3.026
	3-hour	0.800	0.917	1.296	1.559	1.905	2.173	2.448	2.732	3.121	3.428
	6-hour	0.774	0.891	1.290	1.589	2.012	2.362	2.744	3.161	3.773	4.288
	12-hour	0.753	0.879	1.312	1.639	2.105	2.494	2.920	3.389	4.082	4.669

Hourly region	Duration	RGFs for selected AEP (%)									
		63.29	50.00	20.00	10.00	4.00	2.00	1.00	0.50	0.20	0.10
9	60-minute	0.772	0.912	1.354	1.652	2.035	2.324	2.615	2.910	3.305	3.608
	2-hour	0.771	0.914	1.362	1.661	2.041	2.324	2.608	2.891	3.268	3.555
	3-hour	0.771	0.920	1.376	1.673	2.043	2.314	2.579	2.841	3.182	3.437
	6-hour	0.751	0.904	1.385	1.711	2.129	2.444	2.762	3.083	3.515	3.846
	12-hour	0.751	0.911	1.401	1.724	2.131	2.431	2.727	3.021	3.408	3.698
10	60-minute	0.817	0.940	1.310	1.547	1.837	2.046	2.247	2.444	2.695	2.879
	2-hour	0.814	0.936	1.309	1.550	1.850	2.068	2.281	2.490	2.761	2.963
	3-hour	0.819	0.943	1.314	1.547	1.830	2.031	2.223	2.408	2.642	2.811
	6-hour	0.810	0.945	1.340	1.584	1.873	2.075	2.266	2.446	2.670	2.829
	12-hour	0.803	0.940	1.346	1.600	1.906	2.122	2.328	2.525	2.773	2.951
11	60-minute	0.877	0.979	1.256	1.412	1.581	1.689	1.785	1.869	1.965	2.028
	2-hour	0.838	0.949	1.279	1.488	1.740	1.921	2.093	2.260	2.471	2.624
	3-hour	0.830	0.939	1.276	1.497	1.774	1.978	2.179	2.378	2.638	2.834
	6-hour	0.835	0.942	1.271	1.484	1.751	1.946	2.137	2.326	2.571	2.754
	12-hour	0.770	0.898	1.319	1.623	2.035	2.364	2.711	3.078	3.598	4.019

Glossary

(All definitions are given relative to precipitation frequency analyses in NOAA Atlas 14)

ANNUAL EXCEEDANCE PROBABILITY (AEP) – The probability associated with exceeding a given amount in any given year; the inverse of AEP provides a measure of the average time between *years in which a particular value is exceeded at least once*; the term is associated with analysis of annual maximum series (see also AVERAGE RECCURENCE INTERVAL).

ANNUAL MAXIMUM SERIES (AMS) – Time series of the largest precipitation amounts in a continuous 12-month period (calendar or water year) for a specified duration at a given station.

ArcInfo ASCII GRID (a.k.a. ESRI ASCII grid) – Grid format with a 6-line header, which provides location and size of the grid and precedes the actual grid data. The grid is written as a series of rows, which contain one ASCII integer or floating point value per column in the grid. The first element of the grid corresponds to the upper-left corner of the grid.

AVERAGE RECURRENCE INTERVAL (ARI; a.k.a. RETURN PERIOD, AVERAGE RETURN PERIOD) – Average time between *cases of a particular precipitation magnitude* for a specified duration and at a given location; the term is associated with the analysis of partial duration series. However, ARI is frequently calculated as the inverse of AEP for the annual maximum series; in this case it represents the average period between years in which a given precipitation magnitude is exceeded at least once.

CASCADE, RESIDUAL ADD-BACK (CRAB) – The HDSC-developed spatial interpolation procedure for deriving grids of precipitation frequency estimates from grids of mean annual maxima and point precipitation frequency estimates for a given duration.

CONSTRAINED OBSERVATION – A precipitation measurement or observation bound by clock hours and occurring in regular intervals. This observation requires conversion to an unconstrained value (see UNCONSTRAINED OBSERVATION) because maximum 60-minute or 24-hour amounts seldom fall within a single hourly or daily observation period.

DATA YEARS – See RECORD LENGTH.

DEPTH-DURATION-FREQUENCY (DDF) CURVE – Graphical depiction of precipitation frequency estimates (one curve per frequency) in terms of depth (y-axis) and duration (x-axis).

DISCORDANCY MEASURE – Measure used for data quality control and to determine if a station is consistent with other stations in a region. It is calculated for each station in a region as the distance of a point in a 3-dimensional space represented by at-site estimates of three L-moment ratios (L-CV, L-skewness, and L-kurtosis) from the cluster center that is defined using the unweighted average of the three L-moment ratios from all stations within the region.

DISTRIBUTION FUNCTION (CUMULATIVE DISTRIBUTION FUNCTION) – Mathematical description that completely describes frequency distribution of a random variable, here precipitation. Distribution functions commonly used to describe precipitation data include 3-

parameter distributions such as Generalized Logistic (GLO), Generalized Extreme Value (GEV), Generalized Normal (GNO), Generalized Pareto (GPA), and Pearson type III (PE3), the 4-parameter Kappa distribution, and the 5-parameter Wakeby distribution.

FEDERAL GEOGRAPHIC DATA COMMITTEE (FGDC) COMPLIANT METADATA – A document that describes the content, quality, condition, and other characteristics of data and follows the guidelines set forth by the FGDC; metadata is "data about data."

FREQUENCY – General term for specifying the average recurrence interval or annual exceedance probability associated with specific precipitation magnitude for a given duration.

FREQUENCY ANALYSIS – Process of derivation of a mathematical model that represents the relationship between precipitation magnitudes and their frequencies.

FREQUENCY ESTIMATE – Precipitation magnitude associated with specific average recurrence interval or annual exceedance probability for a given duration.

HETEROGENEITY MEASURE, H1 – Measure that is used to assess regional homogeneity, or lack thereof. It is based on comparison of the variability of sample estimates of coefficient of L-variation in a region relative to their expected variability obtained through simulations.

INDEX FLOOD – The mean of the annual maximum series at each observing station.

INDEX FLOOD REGIONAL FREQUENCY ANALYSIS - Regional frequency analysis approach that assumes that all stations in a homogeneous region have a common regional growth curve that becomes location-specific after scaling by a site-specific index flood value. The name comes from its first applications in flood frequency analysis but the method is applicable to precipitation or any other kind of data.

INTENSITY-DURATION-FREQUENCY (IDF) CURVE – Graphical depiction of precipitation frequency estimates (one curve per frequency) in terms of intensity (y-axis) and duration (x-axis).

INTERNAL CONSISTENCY – Term used to describe the required behavior of the precipitation frequency estimates from one duration to the next or from one frequency to the next. For instance, it is required that the 100-year 3-hour precipitation frequency estimates be greater than corresponding 100-year 2-hour estimates.

L-MOMENTS – L-moments are summary statistics for probability distributions and data samples. They are analogous to ordinary moments, providing measures of location, dispersion, skewness, kurtosis, and other aspects of the shape of probability distributions or data samples, but are computed from linear combinations of the ordered data values (hence the prefix L).

MEAN ANNUAL PRECIPITATION (MAP) – The average precipitation for a calendar year based on the period of record. In NOAA Atlas 14 Volume 4, the mean annual precipitation estimates for 1971-2000 were used as a predictor grid for interpolating mean annual maximum precipitation estimates.

PARTIAL DURATION SERIES (PDS) – Time series that includes all precipitation amounts for a specified duration at a given station above a pre-defined threshold regardless of year; it can include more than one event in any particular year.

PRECIPITATION FREQUENCY DATA SERVER (PFDS) – The on-line portal for all NOAA Atlas 14 deliverables, documentation, and information; http://hdsc.nws.noaa.gov/hdsc/pfds/.

PARAMETER-ELEVATION REGRESSIONS ON INDEPENDENT SLOPES MODEL (PRISM) – Hybrid statistical-geographic approach to mapping climate data developed by Oregon State University's PRISM Group.

QUANTILE – Generic term to indicate the precipitation frequency estimate associated with either ARI or AEP.

RECORD LENGTH – Number of years in which enough precipitation data existed to extract meaningful annual maxima in a station's period of record (or data years).

REGIONAL GROWTH FACTOR (RGF) – A quantile of a regional dimensionless distribution (regional growth curve) that becomes a location-specific precipitation quantile after scaling by a site-specific index-flood. For a given frequency and duration, there is a single RGF for each region.

SHAPEFILE – An ESRI vector file format for displaying non-topological geometry and attribute information for use with Geographical Information Systems (GIS). A shapefile has a .shp extension and comes with other associated files, including *.shx, *.sbx, *.sbn and *.dbf.

UNCONSTRAINED OBSERVATION – A precipitation measurement or observation not bound by clock hours but rather based on a moving window through time.

WATER YEAR – Any 12-month period, usually selected to begin and end during a relatively dry season. In NOAA Atlas 14 Volume 4, it is defined as the period from October 1 to September 30.

References

Bonnin, G., D. Martin, B. Lin, T. Parzybok, M. Yekta, and D. Riley, 2004: Precipitation Frequency Atlas of the United States, Semiarid Southwest, *NOAA Atlas 14, Volume 1,* National Weather Service, Silver Spring, Maryland.

Bonnin, G., D. Martin, B. Lin, T. Parzybok, M. Yekta, and D. Riley, 2004: Precipitation Frequency Atlas of the United States, Ohio River Basin and Surrounding States, *NOAA Atlas 14, Volume 2,* National Weather Service, Silver Spring, Maryland.

Bonnin, G., D. Martin, B. Lin, T. Parzybok, M. Yekta, and D. Riley, 2006: Precipitation Frequency Atlas of the United States, Puerto Rico and the U.S. Virgin Islands, *NOAA Atlas 14, Volume 3,* National Weather Service, Silver Spring, Maryland.

Dalrymple, T., 1960: Flood Frequency Analyses, Manual of Hydrology: Part 3, Flood Flow Techniques, *USGS Water Supply Paper 1543-A*.

Daly, C., and R.P. Neilson. 1992: A Digital Topographic Approach to Modeling the Distribution of Precipitation in Mountainous Terrain, *Interdisciplinary Approaches in Hydrology and Hydrogeology*, American Institute of Hydrology, 437-454.

Daly, C., W.P. Gibson, G.H. Taylor, G.L. Johnson, and P.Pasteris, 2002: A knowledge-based approach to the statistical mapping of climate. Climate Research, 23, 99-113.

Durrans, S.R., and P.A. Brown, 2002: Development of an Internet-Based Rainfall Atlas for Alabama. *Water Science and Technology*, 45/2, 11-17.

Everitt, B. S., S. Landau, and M. Leese, 2001: *Cluster Analysis*, 4th edition, Edward Arnold Publishers, 229 pp.

Hirsch, R. M., R. B. Alexander, R. A. and Smith, 1991: Selection of Methods for the Detection and Estimation of Trends in Water Quality, *Water Resources Research*, 27, 803-814.

Hosking, J.R.M. and J.R. Wallis, 1997: *Regional Frequency Analysis, An Approach Based on L-Moments*. Cambridge University Press, 224 pp.

Huff, F. A., 1967: Time Distribution of Rainfall in Heavy Storms, *Water Resources Research*, 3(4), 1007-1019.

Interagency Advisory Committee on Water Data, 1982: Guidelines for Determining Flood Flow Frequency, *Bulletin 17B of the Hydrology Subcommittee*, Office of Water Data Coordination, U.S. Geological Survey, Reston, VA., 183 pp.

Langbein, W. B., 1949: Annual Floods and the Partial-duration Flood Series, *Transactions American Geophysical Union*, 30, 879-881.

Laurenson, E.M., 1987: Back to Basics on Flood Frequency Analysis. *Civil Engineers Transactions*, Institution of Engineers, Australia, CE29, 47-53.

Maidment, D. R., 1993: *Handbook of Hydrology*. McGraw-Hill Publishing.

McQueen, J., 1967: Some Methods for Classification and Analysis of Multivariate Observations, *Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability*, Vol. 1, University of California Press, 281-297.

Miller, J.F., R.H. Frederick and R.J. Tracy, 1973: Precipitation-Frequency Atlas of the Western United States. *NOAA Atlas 2*, Volumes 1-11, National Weather Service, Silver Spring, Maryland.

Myers, V.A. and R.M. Zehr, 1980: A Methodology for Point-to-Area Rainfall Frequency Ratios. *NOAA Technical Report NWS 24,* Office of Hydrology, National Weather Service, Silver Spring, Maryland.

Neteler, M. and H. Mitasova. 2002: *Open Source GIS: A GRASS GIS Approach*, Kluwer Academic Publishers, Boston.

Parzybok, T. and M. Yekta, 2003: NOAA/NWS Precipitation Frequency Data Server. *19th International Conference on Interactive Information Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology*, 83rd American Meteorological Society Annual Meeting, Long Beach, California.

Plantico, M.S., L.A. Goss, C. Daly, and G. Taylor, 2000: A New U.S. Climate Atlas, *Proceedings of the 12th AMS Conference on Applied Climatology,* American Meteorological Society Annual Meeting, Asheville, North Carolina.

USDA-NRCS, 1998: *PRISM Climate Mapping Project--Precipitation. Mean Monthly and Annual Precipitation Digital Files for the Continental U.S.*, USDA-NRCS National Cartography and Geospatial Center, Ft. Worth TX.

U.S. Weather Bureau, 1962: Rainfall-Frequency Atlas of the Hawaiian Islands for Areas to 200 Square Miles, Durations to 24 Hours, and Return Periods from 1 to 100 Years, *Technical Paper No. 43*, Washington D.C., 60 pp.

U.S. Weather Bureau, 1965: Two- to Ten-Day Rainfall for Return Periods of 2 to 100 Years in the Hawaiian Islands, *Technical Paper No. 51*, Washington D.C., 34 pp.

Zehr, R.M., and V.A. Myers, 1984: Depth-Area Ratios in the Semi-arid Southwest United States. *NOAA Technical Memorandum NWS HYDRO-40*, Office of Hydrology, National Weather Service, Silver Spring, Maryland.