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Frequency Analysis of Daily Rainfall Maxima For Central and South Florida

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by

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EXECUTIVE SUMMARY

Rainfall frequency analysis and rainfall maps for short storm durations and various return periods pertaining to Central and South Florida are used for design, regulatory and hydrologic applications. Periodic updating of these analyses and maps is essential when additional data and new technologies become available. The objective of this study is to update the existing rainfall frequency analysis by using up-to-date data and detailed analysis, and to prepare maps showing contours of rainfall depths (isohyetal maps) for selected durations and return periods.

The South Florida Water Management District collects and archives rainfall data from various rain gages. The daily rainfall data collected between January 1, 1900 to December 31, 1999, a period of 100 years, were used for this study. Three sets of rainfall gage records for one-day, three-day and five-day durations were used in determining the maximum rainfall over their respective period-of-record. The maximum recorded rainfall varied from four to 18 inches for the one-day duration; six to 20 inches for the three-day duration; and eight to 22 inches for the five-day duration. Central and South Florida was affected by 38 hurricanes and 23 tropical storms from 1900 to 1999. Of these 61 rainfall events, 59 were recorded in the District's database. The decade with the maximum number of rainfall events was the 1940s with 11 events recorded and a minimum of two events occurred in the 1970 decade. The range of maximum rainfall was between 23.5 and 2.0 inches; and the average and standard deviation were 11.5 and 5.0 inches, respectively. An analysis indicates that 5, 25, 50, 75 and 85 percent of the rainfall events produced rainfall amounts greater than 22.0, 16.0, 13.0, 10.0 and 8.0 inches, respectively.

For frequency analysis, a total of 86, 66 and 65 stations was selected for one-day, three-day, and five-day durations, respectively. A significant number of these stations has time series of daily rainfall for more than 50 years. For the selected stations, the annual or partial duration series were constructed. Seven probability distributions were applied to the annual or partial annual series of the each selected station. Based on the established best-fit criteria, a probability distribution was chosen to fit the annual series data of each selected station. The results provided the rainfall depths for various return periods at each station. This process was applied to all the three rainfall durations. The results of the frequency analysis provided the rainfall estimates for six return periods and three durations. Several isohyetal maps for six return periods and three durations were prepared using the Kriging interpolation method.

This study updates District's previous two studies (i.e., 1981 and 1990). As expected, the rainfall estimates generated in this study were different from those studies. In summary, rainfall estimated in this study were higher in the middle and lower parts of the Lower West Coast areas and lower part of the Lower East Coast areas. Whereas, the rainfall estimates were lower in the upper portion of the Lower East Coast areas. Furthermore, it was observed that the rainfall data of short durations exhibit significantly larger temporal and spatial variability compared to monthly or annual rainfall. This updated frequency analysis and isohyetal maps of short duration rainfall is expected to be used for various designs, regulations and hydrologic and hydraulic analyses in Central and South Florida.

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INTRODUCTION

Background

The South Florida Water Management District (District) manages water resources on approximately 18,000 square miles of land. This land area is in South Florida and portions of Central Florida. The area has a very flat topography with the Atlantic Ocean on the east and the Gulf of Mexico on the west. The land area has unique hydrological characteristics that include a high density of rivers, streams, lakes, canals and wetlands. The area climate is characterized as semitropical. The rainfall events over the District area are an important and integral part of the water resources system.

During the year, typically, sea breezes from both coasts over the hot land surface cause the formation of intense storms inland. In addition, some of the high rainfall events occur from the hurricanes and tropical storms that strike Florida. Hurricanes and tropical storms generally produce tremendous amounts of rainfall, and coastal regions are more likely to experience these rainfall events. At the District, the data of the last 113 years (1886 to 1998) indicate that about 80 percent of the hurricane and tropical storm events occur in August, September and October. Some of the heaviest rainfalls in Central and South Florida are generated by convective systems with the cooler season having an extra-tropical nature and the warm season having a tropical origin.

Based on the temporal rainfall patterns in this region, the period from November through April is considered the dry season, and June through September is considered the wet season. However, May and October are transitional months, having rainfall from both wet and dry season regimes. Long-term averages indicate that two-thirds of the annual rainfall occurs during the wet season. Previous studies, at the District, reported that the decades of 1970 and 1980 tended to be drier, while the decade of 1990 tended to be a wetter one (as noted in this study).

In addition, the rainfall amounts vary geographically within Central and South Florida. The rainfall characteristics over Lake Okeechobee and the surrounding ocean are different from that of overland mass. Based on monthly, seasonal and annual rainfall data, the spatial variations in the rainfall amounts are unique within the area of the District. Spatial variations reduce as rainfall duration increases. The Palm Beach County area has the highest annual rainfall whereas the lower Kissimmee River and Lake Okeechobee areas have the lowest annual rainfall. The Southwest Coast area has unique characteristics with the highest and lowest average rainfall for wet and dry seasons respectively. The dry season rainfall varies with the lowest in the Southwest Coast and highest in Palm Beach County. Generally, spatial variation in rainfall amounts for shorter durations, such as one-, three-, and five- day, is significantly greater than month, season and annual rainfall.

Scope of Work

Rainfall frequency analysis and rainfall maps for storm durations of one-, three-, and five-day for various return periods pertaining to Central and South Florida are used as references (MacVicar, 1981, and Trimble, 1990) for design, regulatory and hydrologic applications. Periodic updating of these studies is essential when additional data and new technology become available.

The objective of this study is to update the existing rainfall frequency analysis by using up-to-date data and detailed analysis, and to prepare isohyetal (contours of rainfall depths) maps. This study used the available rainfall data from January 1, 1900 to December 31, 1999 within the 16 counties for the analysis. However, the areas located within the Key West islands and Lake Okeechobee were excluded.

PREVIOUS RELATED STUDIES

Hershfield (1961) published the results of a comprehensive rainfall frequency analysis and mapping for the entire United States. In the study, the rainfall estimates for several storm durations from 1 to 24 hours were performed and presented. The analysis used the data through 1957 from recording rain gages and through 1958 from a non-recording rain gage network. The Gumbel distribution (also known as Fisher Tippett Type I distribution) was used in the analysis. Miller (1964) published the results of a similar analysis and mapping for rainfall durations from two to 10 days for the contiguous United States in the Technical Paper No. 49. In this study, the rainfall data through 1961 was used for the analysis.

For South and Central Florida, the US Army Corps of Engineers (1953) prepared a design memorandum on the rainfall frequency estimates. This study used the rainfall data through 1952 and performed frequency analysis for various storm durations from one-day to one-year and for return periods from two- to 100 -years.

MacVicar (1981) performed a frequency analysis of rainfall for the South and Central Florida area for the District. The study used 140 stations with an average period of record of 33 years. The stations with more than 150 days of missing values were excluded from this analysis. The annual series and partial duration series were used in the analysis. However, no adjustments were made to the return period estimates, which were derived from the partial duration series. Two frequency distributions, Gumbel distribution (also known as Fisher Tippett Type I distribution) and Log Pearson Type III distribution, for one-day rainfall duration were tested and compared. It was determined that the Gumbel distribution fitted more often. The study developed several isohyetal maps using results of the Gumbel distribution. The isohyetal maps for the durations of one-day, two-day, three-day, five-day, dry season, wet season and annual periods at the return periods of three-, five-, 10-, 25-, 50-, and 100- year were prepared.

Sculley (1986) conducted a frequency analysis of wet season, dry season and annual rainfall for the District. The project used regional rainfall data from 1915 to 1985. The regional average annual rainfall for 71-year period within the District was 53 inches. The minimum and maximum annual rainfalls were 39 and 77 inches, which fell in 1956 and 1947 respectively. These annual rainfall amounts were averages of basin rainfall amounts over the District and did not reflect the spatial variability. The statistical goodness of fit tests indicated that the District annual rainfall followed a Log-Normal distribution. Based on the results of the study, the 77 inches of rainfall recorded in 1947 exceeded the 1 in 200-year event; whereas the 39 inches of rain in 1956 were between the 1 in 50-and 1 in 100-year event. The study found that approximately two-thirds of annual rain falls in wet season (i.e., June through October).

The maximum rainfall depths, for one- and three-day storm duration at the return periods of five-, 10-, 25- and 100- year, are the most commonly used (by the Surface Water Management Division, Regulation Department of the District) in the permit review process as described in the Management and Storage of Surface Waters, Permit Information Manual, Volume IV (1989).

Trimble (1990) performed a frequency analysis of one and three-day rainfall maxima for the District. This study updated the MacVicar (1981) study. The study used data from a total of 156 gage stations. These stations had at least 20 years of daily data available. The study used 21 percent more station-years than used in the previous study. An examination of the long-term rainfall gage stations representing different regions of the District revealed that June and September generally have the highest probability of occurrence of annual maxima for one- and three- day duration storm events. The two-parameter Gumbel distribution was used in this frequency analysis. Based on the results of the analysis, isohyetal maps for the three-, five-, 10-, 25- and 100-year return periods for the one-and three-day storm duration were prepared.

Abtew et al. (1993) compared six methods used in the spatial analysis of monthly rainfall in South Florida. The results of the study indicated that the multi-quadric, Kriging and optimal interpolation are the best three methods for spatial interpolation of monthly rainfall. The Kriging method uses the variogram function; the optimal interpolation method uses the spatial correlation function. Both methods are related and provide good estimates of the interpolation errors. Either of the two methods is the best estimator of monthly point and areal rainfall in the study area.

Van Lent and Tracy (1994) performed an assessment of the rain gage network in the District using the geo-statistical analysis. The study found that the experimental variograms for wet and dry season and annual rainfall are an isotropic and stationary process with a correlation length of about 19 miles (30 kilometers). Concern about these findings was documented by Ali et al. (1999) and Moss (1996). Moss (1996) indicated that a discrepancy existed between the annual variogram plot and associated equation. This study reported that the monthly variogram are intrinsic but dominated by a nugget effect. The current rain gage network is unable to detect the scale of variability on a monthly basis. The daily variograms are pure nuggets. The network is unable to detect any difference between the spatial distribution of daily rainfall and white noise. Ali et al. (1999) pointed out concerns regarding the computation method used in variograms for this study. The study concluded that major improvements to the network cannot be made by adding large numbers of new gages. However, three to five new gages are recommended for three sub-areas of the District based on decreasing the estimation error. The three sub-areas are the west coast of Everglades National Park, the upper west coast Cape Coral region, and the Big Cypress Preserve.

Zhao and Chin (1995) also conducted an assessment of the evaporation and rain gage network using spatial analysis of monthly rainfall and evaporation. The experimental monthly variograms presented good spatial coherence and the exponential model was developed with a reasonable fit. An experimental variogram was computed as the average of all historical realization of variograms. Ali et al. (1999) suggested that such a computation needs to be tested for the assumption that the stationarity of the second order for each realization, and may not require ergodicity assumption. Furthermore, this study indicated that the variogram range was similar to that found by Van Lent and Tracy (1994). Ali et al. (1999) recommended that any conclusion derived from these assumptions should be re-evaluated in this study.

Wanielista et al. (1996) developed isopluval contour curves for Florida. The curves were for one- , two- , three- , four-, seven- and 10- day storm durations at return periods of two-, five-, 10-, 25-, 50- and 100- years. The curves fitted six probability distributions to rainfall data at 25 sites. It was reported that the two-parameter Log Normal and the Log Pearson Type III distributions gave the best fit for the rainfall data for various durations. The study used data from 56 rain gage stations and used Log-Pearson Type III distribution for the frequency analysis. The estimated rainfall volumes for each duration and return period for each station were used in contour plotting. In plotting contours, a Kriging procedure was used to interpolate and extrapolate values for areas where no gage stations were used in the analysis. In addition, the study compared its results with Technical Paper 40 and four Florida water management districts' studies. The data from approximately 17 stations, located within the District boundaries, were used in the study. The study compared results of 15 common stations with the District's Trimble (1990) study. The comparison showed that nine stations had slightly lower values; four stations had slightly higher values; and two stations had much higher values than the District study. The study also compared skewness coefficients for three locations. The skewness varied at each location depending on the number of years of data included in the data set. The skewness fluctuations were somewhat larger for smaller data sets (10 to 25 years of data), however, for larger data sets, the skewness coefficients converged to a small range of numbers. The skewness coefficients of 0.4, 1.3 and 2.3 were reported for Apalachicola, Jacksonville and Miami areas respectively.

Abtew (1996) studied frequency distribution of a point rainfall in the District and generated synthetic data. The study used daily historical rainfall data (38 years from 1957 to 1995) from a rain gage and fitted with a two-parameter Gamma distribution for daily rainfall for each month. One-hundred-year synthetic daily rainfall data were generated using the statistical parameters of the historical data. The WGEN model (Richardson and Wright, 1984) was used for synthetic data generation.

Ali et al. (1999) conducted frequency and spatial analyses for monthly rainfall for the District. Based on a prescribed procedure for temporal and spatial representative data, 145 sites with the records of 25 years or more were selected. Based on the best fit for the frequency analysis, a two-parameter Gamma distribution was selected among seven probability distributions. Rainfall estimates were computed using the selected distribution at the 145 sites for various return periods. These estimates were used for spatial analysis that included development of experimental variograms and fitting of exponential variograms for each month and each return period. Using the variogram models and estimated rainfall data, maps were prepared using ordinary Kriging for monthly rainfall values for various return periods.

Ali and Abtew (1999) performed a frequency analysis for each of the 14 rainfall basins, which are used for managing water resources of the District. The analysis was conducted on monthly, dry and wet seasons, and annual basin areal rainfall. The results indicated that monthly, dry season and wet season basin areal rainfall fitted a two-parameter Gamma distribution, whereas the annual basin rainfall fitted the Log-Normal distribution. The rainfall depths were estimated, based on the selected distribution, for five-, 10-, 20-, 50-, and 100-year dry and wet return periods. Rainfall estimates for 100-year wet return period range between 15 and 23 inches for June for all basins, whereas the range varies from 11 to 20 inches for remaining wet season months (July through October). Histograms and basic statistics indicate that the Southwest Coast area has the lowest and highest average rainfall for the dry and the wet seasons respectively. The Palm Beach County area has the highest annual average rainfall, whereas Lower Kissimmee and Lake Okeechobee areas have the lowest annual average rainfall. On an average, 35 percent of the annual District rainfall occurs in the dry season. The annual percentage of dry season rainfall varies from basin to basin with the lowest in the Southwest Coast at about 29 percent and the highest in the Palm Beach County area at about 39 percent.

RAINFALL DATA

Data Sources

Several hundred rainfall gages are within the District boundaries. The rainfall data are gathered from various recording and non-recording gages. The network of rainfall gages covers Central and South Florida. Federal, state and local government agencies including the District are involved in collection of rainfall data and maintenance of rainfall gages. Some of the agencies involved in these activities include National Oceanic and Atmospheric Administration (NOAA); U.S. Geological Survey (USGS); U.S. Army Corps of Engineers (COE); U.S. National Park Service; and Florida Forestry Service. In addition, many cities and counties within the District monitor rainfall.

The District collects rainfall data from its gages within its 16-county water management area. Primarily, four types of instruments are used for rainfall measurement. The instruments include manually read rain gage, calibrated stilling well rain gage, weighing bucket rain gage, and tipping bucket rain gage. Four methods are used for data acquisition from the instruments. These data acquisition methods include manual (i.e., manual logging), mechanical (i.e., punched tape logging), electronic (i.e., solid state electronic equipment logging), and telemetry (i.e., microwave and radio equipment logging). In addition, the operation and maintenance department of the District has capability to estimate daily (on 24-hour basis) rainfall data from radar system for the entire District. However, these daily rainfall estimates are archived on a rotating basis for last two or three years only. Presently, this radar data is not archived in the District database and is not used in this study.

In addition, the District acquires rainfall data from above mentioned government agencies through various mechanisms, including direct contracts, cost-sharing agreements, and data exchange agreements. The rainfall data are stored in the DBHYDRO, a computer database, at the District headquarters. The District uses Oracle relational database management system to store and retrieve various hydrological data including rainfall data.

Gage Network

Queries on DBHYDRO indicate those rainfall data records for 1,701 gage records are archived. A majority of the rain gages listed (in DBHYDRO) are distinct sites. However, there are a number of gages having a duplicate listing for the same site. Each gage record, which is a listing for a rainfall data, has a unique five-character alphanumeric (database) identification number known as a dbkey. A duplicate listing of gages exists due to changes in rain gage equipment and/or change in the agency collecting the data. Due to these reasons, the duplicate rain gage listings (in DBHYDRO) would show separate periods of record associated with the same gage location.

The rain gage records (in DBHYDRO) include data for various frequencies and statistical types. The records include daily rainfall sum, monthly rainfall sum, random interval rainfall sum, or instantaneous rainfall. **Table 1** shows rainfall data in DBHYDRO on various frequencies, statistical type and number of gage records. In addition, each gage record has relevant site information such as station name, alternate identification, agency, county, recorder type, station description, dbkey number, site latitude and longitude, and state plane x and y coordinates of site.

Table 1
Types and Frequencies of Rainfall Records in DBHYDRO

Frequency	Type	No. of Gage Records
Random	Daily Wet Records (DWR)	51
Breakpoint	Instantaneous	466
Daily	Sum	1071
Monthly	Sum	85
Random	Sum	28
TOTAL		1701

Gage Record Selection

Initial selection of gage records involved using any gage listing with daily rainfall records. This criterion provided 1,071 gage records. Due to the availability of the large numbers of gage records of daily rainfall, breakpoint rainfall data were not selected in this analysis.

The review of the period-of-record of those selected indicate that January 1, 1900, is the earliest date for which daily rainfall data are available in DBHYDRO. However, the rainfall data was collected and reported by NOAA at nine sites in south Florida between 1832 and 1900. **Table 2** shows the available number of gage records with daily rainfall and their respective length of period-of-record.

For this analysis, the daily rainfall data between January 1, 1900, to December 31, 1999, a period of 100 years, were used. However, gage records with a continuous 100-year of period-of-record are not available. Only seven gage records with over a 90-year of period-of record are available. Some data was missing in those records as well.

The spatial locations of all the rain gage stations with 1071 gage records in the DBHYDRO are shown in **Appendix A (Figure A-1)**. The station identification (x and y coordinates and station names) and their respective dbkeys of these rain gages presented in **Appendix B**.

Table 2
Availability of Daily Rainfall Data

Years of Daily Rainfall Data Available (equal to or greater than)	Number of Gage Records
1	982
10	478
20	319
30	216
40	117
50	64
60	31
70	21
80	14
90	7
100	0

Table 3
Tags Succeeding Daily Rainfall Data

Tag	Tag Descriptions
!	Questionable and/or Exceed the Range
>	Greater Than
<	Less Than
A	Accumulated (Includes Previous Days with X)
E	Estimated
M	Missing Data
N	Not Processed Yet
P	Partial Record
R	Rainfall Was Recorded (Exact Amount Unknown)
T	Trace Amount (Not Enough to Measure Accurately)
X	Unknown and Included in Next Amount Tagged "A"

Data Quality

It is difficult to quantitatively assess the quality of daily rainfall data. However, the rainfall data quality, for most gage records available from DBHYDRO, appears to be good. In DBHYDRO, each daily rainfall value may be tagged with "null" or a single character. **Table 3** shows a listing of tags used and their respective meaning. The tag "!" with a rainfall value indicates that the value is questionable and/or exceeds the pre-established range. When a daily rainfall value is "null" and it is tagged with the letter "X", it represents unknown data for that day at the gage station. The tag "A" with a rainfall value indicates cumulative amount of rain for the days where the rain values are unknown, marked with "X" tags. When a daily rainfall value is "null", it is tagged with the letter "M," it represents missing data at the gage station in question. The DBHYDRO was queried for missing daily rainfall data and the results are presented in **Table 4**. **Table 4** shows the number of gage records with equal to or less than percent of missing data from their period-of-record. In DBHYDRO, 95 percent of the gage records with daily data has less than or equal to 10 percent of missing data.

Table 4
Extent of Missing Daily Rainfall Data

Percent Missing Data From Period-of-Record (less than or equal to)	Number of Gage Records	Percent of Gage Records
0.0	134	42
1.0	220	69
5.0	287	90
10.0	302	95
60.0	319	100

Data Limitations

Several limitations exist in measuring the accurate rainfall data. These limitations come from varieties of sources that influence the accuracy in recording the data. The physical obstructions -- such as trees, buildings, flow measurement structures and others located in the immediate vicinity of recording instrument -- influence the rainfall data. Also, changing weather conditions, such as wind speed or wind direction during the rainfall event, impact the rainfall data. It has been reported that the rainfall amounts are under estimated due to wind and are under estimated as much as 1 percent (of rainfall) per mile per hour (of wind speed). The errors in data measurements could come from malfunction of instruments including power surge, power failure, mechanical mechanism and/or electronic system failure, and require re-calibration. In a few cases, instruments may not be capable of measuring very high rainfall amounts, for example, measuring more than 24 inches of rainfall in a one-day period. Some errors in rainfall data are also introduced in data handling phase. These data errors are mostly human incorporated errors during data capture, data transmission, data entry, data processing, and data archiving.

In addition, rainfall data measured at a gage site is a point data that represents the data over an area. Based on the spatial characteristics of rainfall in South and Central Florida, it is probable that some of the localized intense storm events, resulting in high rain amounts, may not have been captured by the current rain gage network. Analysis indicates that the daily rainfall data shows a large spatial variation with all most no correlation. However, as the rainfall duration increases from daily to monthly, seasonal or annual, the spatial variation also reduces significantly and becomes explainable through stronger correlation. Therefore, to obtain geographically better representation of daily rainfall data, a denser (than the current) rain gage network is needed. However, due to the large geographical area under the jurisdiction of the District, it is not economically feasible to operate and maintain a dense rain gage network. Several spatial analysis methods are available to characterize and estimate rainfall data over an area from the point rainfall data, and these methods use various assumptions.

In order to perform reliable statistical analysis, selected samples should have a sufficiently large data size that would represent the population characteristics. Therefore, the longest period-of-record for gage records are highly desirable. For period between July 1, 1909, to January 1, 1914 (4.5 years), a significant data gap exists in DBHYDRO. During this period, no rainfall data are available at any gage site within the District.

DATA ANALYSIS OF MAXIMUM RECORDED RAINFALL

In order to determine variability of the maximum rainfall data and spatial distribution of these data, a detailed analysis was required. The maximum rainfall data were obtained from the entire gage records (from DBHYDRO) that consisted of various lengths of period-of-record, overlapping period-of-record, duplicate gage stations and various sources (many agencies).

For the analysis, one-day, three-day, and five-day rainfall durations were used. One-day, three-day, and five-day duration rainfall amounts consist of total rainfall from 24, 72, and 120 - hour period, respectively. In most analyses, the total rainfall amount, for a given (short) duration, is assumed to occur over the entire period of its duration in a given (synthetic or observed distribution) pattern. Therefore, it is expected that the total rainfall amount for a given duration is obtained from hourly rainfall recorded data set. At the District, the hourly or breakpoint rainfall data are available for very limited number of gages and for very short period-of-record. However, the daily rainfall data are available from large number of gages and for sufficiently longer period-of-record. Hence, the daily rainfall data were used for this study. One-day duration rainfall is considered equal to non-zero daily rainfall amounts and assumed to have occurred over 24-hour period. Similarly, non-zero daily rainfall amounts from three and five consecutive days are considered as three-day and five-day duration, respectively.

For this rainfall data analysis, the area within the District is divided in the three geographic regions. The similarity in geographic rainfall patterns and characteristics was the primary reason for dividing the area into the three regions. These regions are identified as east, west and north areas. Furthermore, these regions are closely aligned with the (regional) planning areas and are known as upper and lower east coast, lower west coast and Kissimmee basin. However, the boundaries of the regions and planning areas are slightly different from those of the planning areas. The eastern region primarily includes upper and lower east coast; the western region consists of lower west coast and the northern region lies in the Kissimmee basin.

The east region includes five counties; they are St. Lucie County, Martin County, Palm Beach County, Broward County and Miami-Dade County. The west region has six counties that include Charlotte County, Glades County, Lee County, Hendry County, Collier County and Monroe County. The north region consists of five counties, namely, Orange County, Polk County, Osceola County, Okeechobee County and Highland County.

The daily rainfall gage records were obtained from DBHYDRO, based on the county in which they are located. The gage records were placed in one of the three regions. From daily rain gage records, two more sets of rain gage records for three-day and five-day durations were developed using a set of computer programs (SQL scripts).

Historical Maximum Rainfall

Once the three sets of rainfall gage records for one-day, three-day, and five-day durations were obtained, they were used in determining the maximum rainfall over their respective period of records. One maximum rainfall value for each gage record was obtained. This step was performed for one-day, three-day, and five-day durations. A total of 973 gage records were used to determine the maximum rainfall values. The eastern, western and northern regions used 499, 247 and 227 gage records, (approximately 51, 26 and 23 percent) respectively. **Appendices B, C and D** show the maximum rainfall data for one-day, three-day and five-day durations obtained from all of the gage records available within the District.

One-Day Duration

The maximum rainfall amounts from each gage record for one-day duration were determined. **Appendix E** shows the maximum rainfall for the selected gage records from 1900 to 1999 and for each region, respectively.

The eastern region has recorded maximum rainfall of 18.0 inches. Five locations showed the highest rainfall of 18.0, 17.4, 17.0, 16.4, and 16.0 inches. This region has lower variability in maximum rainfall amounts. More than 20 locations recorded between 10 and 15 inches.

The western region has recorded maximum rainfall of 20.0 inches. Four locations showed the highest rainfall of 20.0, 19.0, 17.0 and 14.5, inches. This region shows moderate variability in maximum rainfall amounts. Six locations recorded rainfall between 10 and 12 inches. Whereas, more than 20 locations recorded between 9 and 10 inches of rainfall.

The northern region has a recorded maximum rainfall of 21.4 inches. Five locations showed the highest rainfall of 21.4, 17.0, 11.0, 10.0 and 10.0 inches. This shows that variability in maximum rainfall is high in this region. However, there were more than 10 locations that recorded between 9 and 10 inches of rainfall.

Three-Day Duration

The maximum rainfall depths for three-day duration for all gage records were computed. **Appendix E** shows the maximum rainfall from 1900 to 1999 for the selected gage record for north, east and west regions, respectively.

The eastern region has recorded maximum rainfall of 32.1 inches. Seven locations showed the highest rainfall of 32.1, 32.0, 26.8, 20.2, 19.6, 19.4, and 19.4 inches. This region has the moderate variability in maximum rainfall amounts. Thirteen locations recorded between 16 and 19 inches of rainfall.

The western region has recorded maximum rainfall of 29.0 inches. The highest four locations showed the highest rainfall of 29.0, 28.0, 21.7, and 16.2 inches. This region showed the highest variability in maximum rainfall amounts. Five locations recorded rainfall between 14 and 16 inches, while, 17 locations recorded between 12 and 14 inches.

The northern region has a recorded maximum rainfall of 13.8 inches. Six locations showed the highest rainfall of 13.8, 13.7, 13.7, 13.5, 13.1 and 13.1 inches. This showed that variability in maximum rainfall is low in this region. Eighteen locations recorded between 11 and 13 inches of rainfall.

Five-Day Duration

The maximum rainfall depths for five-day duration for all gage records were computed. **Appendix E** shows the maximum rainfall from 1900 to 1999 for the selected gage record for north, east and west regions, respectively.

The eastern region has recorded maximum rainfall of 36.6 inches. Five locations showed the highest rainfall of 36.6, 22.0, 21.4, 21.3 and 21.1 inches. This region has the moderate variability in maximum rainfall amounts. Six locations recorded between 19 and 21 inches of rainfall.

The western region has recorded maximum rainfall of 32.3 inches. The highest four locations showed the rainfall of 32.3, 21.9, 18.5 and 18.2 inches. This region showed high variability in maximum rainfall amounts. Five locations recorded rainfall between 15 and 17 inches. While, 14 locations recorded between 13 and 15 inches.

The northern region has a recorded maximum rainfall of 16.5 inches. Six locations showed the highest rainfall of 16.5, 15.5, 15.2, 14.8, 14.7 and 14.6 inches. This showed that variability in maximum rainfall is low in this region. Ten locations recorded between 12 and 14 inches of rainfall.

Data Analysis

In order to compare the upper limits of the maximum recorded rainfall amounts, the four highest recorded rainfall were considered for initial data analysis. **Table 5** shows the four highest recorded rainfalls for all the three durations and for the three regions. The data presented in this table show the raw data obtained from the DBHYDRO. One-day duration maximum rainfall for the eastern region varies between 18.0 and 16.4 inches; 20.0 and 14.5 inches for the western region; and 21.4 and 10 inches for the northern region. Three-day duration maximum rainfall for the eastern region varies between 32.1 and 20.2 inches; 29.0 and 16.2 inches for the western region; and 13.8 and 13.5 inches for the northern region. Five-day duration maximum rainfall for the eastern region varies between 36.6 and 21.3 inches; and 32.2 and 18.2 inches for the western region; and 16.5 and 14.8 inches for the northern region.

It was noted that the three-day duration rainfall amounts were greater than five-day duration rainfall for east and west regions. Specifically, the rainfall of 32.0 and 26.8 inches for three-day duration and 22.0 and 21.4 inches for five-day duration for the eastern region; and the rainfall of 28.0 and 21.7 inches for three-day duration and 21.9 and 18.5 inches for five-day duration for the western region. Similarly, the rainfall of 21.4 and 17.0 inches for one-day duration and 13.8 and 13.7 inches for three-day duration for the northern region. However, these (apparent data) discrepancies are confined to the first, second and third highest recorded rainfall. Whereas, the fourth highest recorded rainfalls for all durations are consistently increasing that is appropriate and desirable. It should be noted that these recorded rainfall amounts are from single gage stations and are extreme and rare events; and could be considered anomalies for varieties of reasons (see "Data Quality" and "Data Limitation" in previous section of this report). This needs further analysis which is provided in next paragraphs.

Table 5
Four Highest Recorded Rainfall for Three Durations
And Three Regions During 1900-1999

Duration	One-Day				Three-Day				Five-Day			
	Highest Rain (inches)				Highest Rain (inches)				Highest Rain (inches)			
Rank	1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th
East	18.0	17.4	17.0	16.4	32.1	32.0	26.8	20.2	36.6	22.0	21.4	21.3
West	20.0	19.0	17.0	14.5	29.0	28.0	21.7	16.2	32.2	21.9	18.5	18.2
North	21.4	17.0	11.0	10.0	13.8	13.7	13.7	13.5	16.5	15.5	15.2	14.8

A frequency analysis of the maximum rainfall data for the entire gage records and for the three durations and three regions was performed. The results are presented in the following three figures and one table. **Figure 1** shows the amount of maximum recorded rainfall by the percent of gage records for the one-day duration. The majority of the gage records have rainfall between 4 and 14 inches. **Figure 2** shows the amount of maximum recorded rainfall by the percent of gage records for the three-day duration. The majority of the gage records have rainfall between 6 and 16 inches. **Figure 3** shows the amount of maximum recorded rainfall by the percent of gage records for the five-day duration. The majority of the gage records have rainfall between 8 and 18 inches.

Further analyses (**Table 6**) indicated that the one-day duration rainfall greater than or equal to 12 inches was observed by 7.3, 3.1, and 2.1 percent of the gage records for east, west and north regions respectively. The three-day duration rainfall greater than or equal to 16 inches was observed by 6.8, 4.1, and 0.0 percent of the gage records for east, west and north regions respectively. The five-day duration rainfall greater than or equal to 18 inches was observed by 3.8, 2.9, and 0.9 percent of the gage records for east, west and north regions respectively.

The spatial mapping of the maximum recorded rainfall for the selected gage stations (as described in the next section of this report) was performed using the Kriging interpolation method for each of the three durations and are presented in next Chapter titled "Spatial Characteristics of Daily Rainfall Maxima" (see **Figures 13, 20 and 27**).

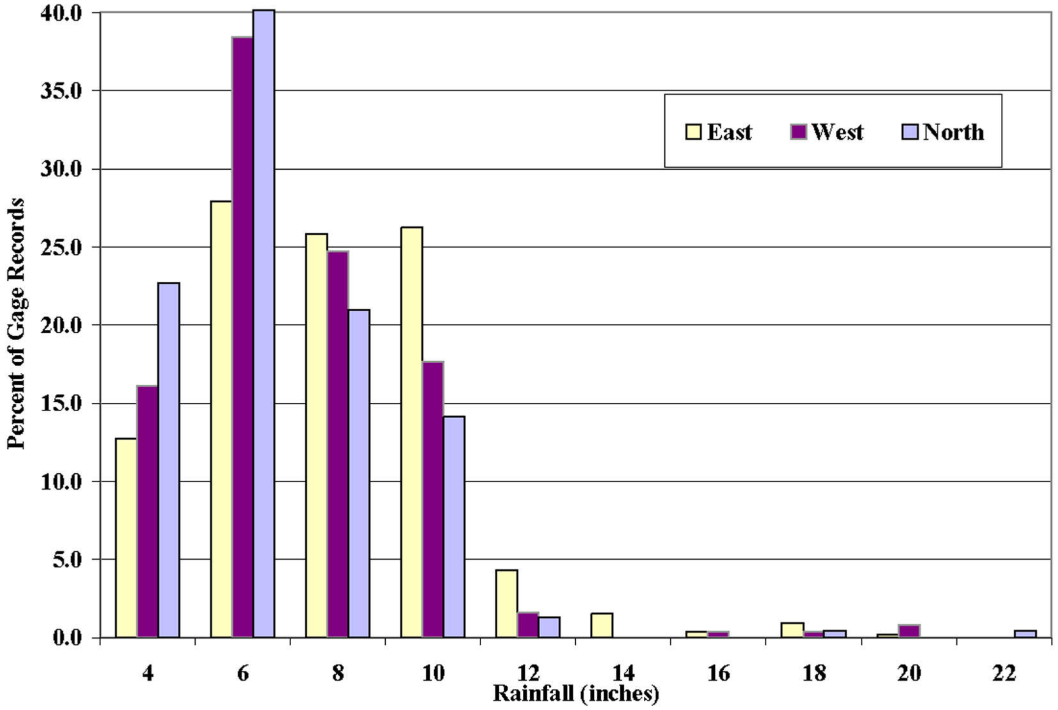


Figure 1. One- Day Maximum Recorded Rainfall During 1900-1999

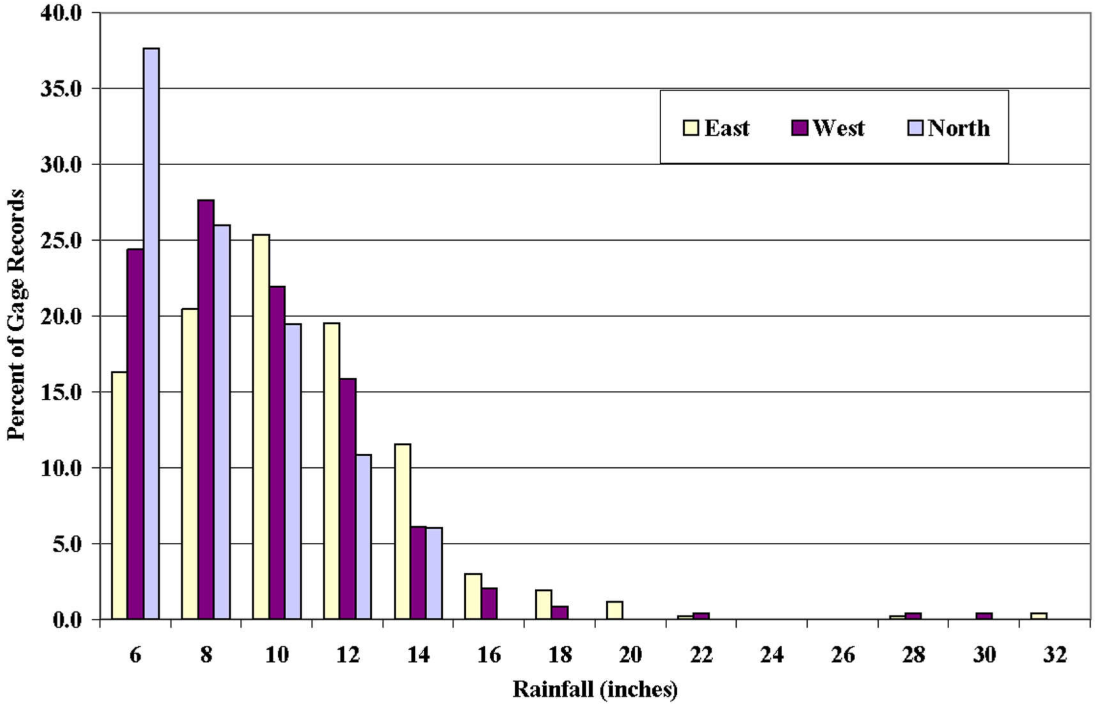


Figure 2. Three- Day Maximum Recorded Rainfall During 1900-1999

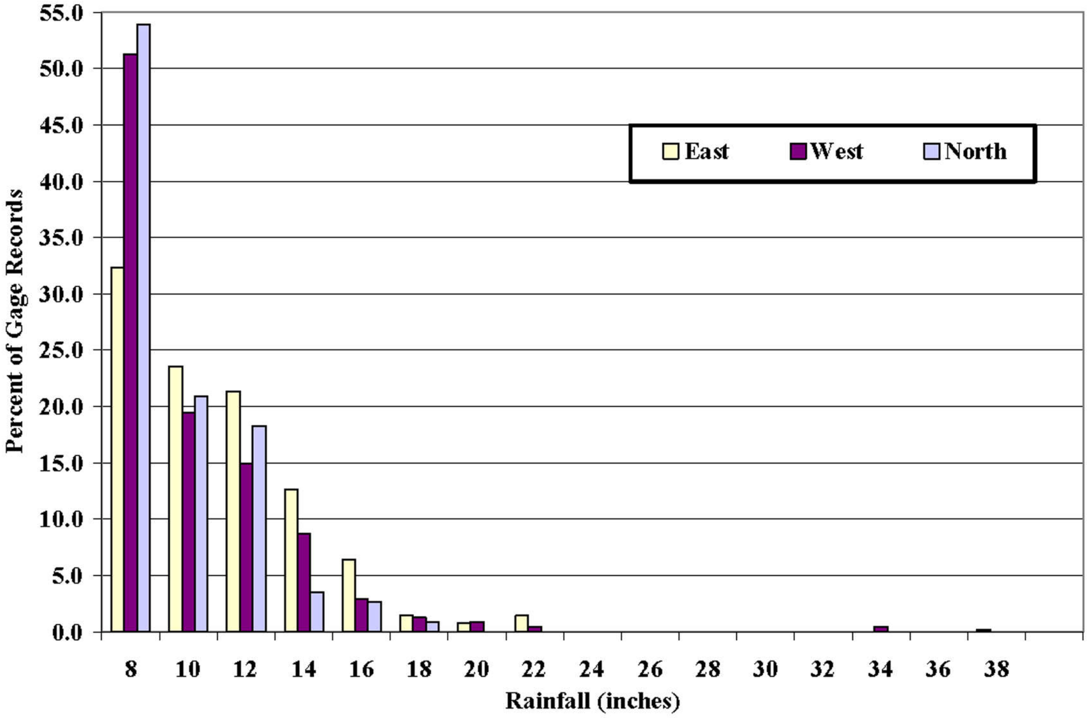


Figure 3. Five- Day Maximum Recorded Rainfall During 1900-1999

Table 6
Percent of Gage Records with Maximum Recorded Rainfall During 1900-1999

Duration	One-Day			Three-Day			Five-Day		
Rainfall (inches) (Equal to Greater Than)	Regions			Regions			Regions		
	East	West	North	East	West	North	East	West	North
10.0	34	21	16	63	48	36	68	49	46
12.0	7	3	2	38	26	17	44	29	25
14.0	3	2	1	18	10	6	23	14	7
16.0	1	2	1	7	4	0	10	6	3
18.0	1	1	1	4	2	0	4	3	1
20.0	0	1	0	2	1	0	2	2	0
22.0	0	0	0	1	1	0	2	1	0

Historical Maximum Rainfall from Hurricanes and Tropical Storms

Several high rainfall events occur due to hurricanes and tropical storms. It was reported that 114 hurricanes and tropical storms (Attaway, 1999) affected the Florida peninsula between 1871 and 1996. Prior to 1886, no distinction was made between hurricanes and tropical storms, and they were known as tropical cyclones. Nine such tropical cyclones were recorded between 1871 to 1886. However, during 1886 to 1900, five hurricanes and 10 tropical storms were observed.

The records indicate that the area within Central and South Florida was affected by 38 hurricanes and 23 tropical storms from 1900 to 1999. A total of 61 rainfall events occurred due to hurricanes or tropical storms in the last 100 years (from 1900 to 1999). The maximum rainfall events occurred in August, September and October, and they were 19, 29, and 29 percent, respectively. These events generated rainfall between one- and 14-day durations. During the decade of 1940 (i.e., between 1940 to 1949), 11 rainfall events, the maximum, were recorded. However, during the decade of 1970, only two rainfall events -- one from a hurricane and one from a tropical storm --the minimum, occurred.

The DBHYDRO was queried for highest rainfall data that occurred during the recorded dates of hurricanes and tropical storms. The rainfall data were available in DBHYDRO from 59 rainfall events out of 61 events. However, the rainfall data were not available (in DBHYDRO) for two hurricanes dated October 11-12, 1909, and October 17 through 19, 1910. **Appendix F** shows the rainfall duration and total maximum rainfall amounts produced from 59 hurricanes and tropical storms in the last 100 years. Attaway (1999) and Neumann et al. (1993) have also reported the maximum rainfall amounts from the hurricanes and tropical storms for most of these events, and they are included in **Appendix F**. Comparison of maximum rainfall amounts obtained from DBHYDRO and the reports by Attaway (1999) and Neumann et al. (1993) indicate that several events have the same maximum rainfall amounts. However, the maximum rainfall amounts obtained from DBHYDRO were higher for many other events. This was due to inclusion of rainfall amounts from the accompanying wet periods (caused by other meteorological activities) continuing before and or after the hurricane or tropical storm event.

Table 7 shows the highest 38 rainfall producing events (greater than 10.0 inches) from the hurricanes and tropical storms in the last 100 years. The first highest rainfall of 23.5 inches occurred in the Fort Lauderdale area over a 13-day duration from the hurricane event during October 16 through 28, 1924. The second highest rainfall of 23.1 inches fell in Collier County over seven-day duration from tropical storm Bob during July 17 through 23, 1985. The top six events (approximately top 10 percent of all the events) produced maximum rainfall of 23.5, 23.1, 20.9, 19.7, 19.6 and 19.2 inches and occurred over six to 13-day durations. **Figure 4** shows the rainfall amounts and spatial location of the rain gage stations that recorded these rainfall events.

Table 7
38 Highest Rainfall Events from Hurricanes and Tropical Storms During 1900-1999

Year	Date	Type of Storm	County	Station	Dbkey	Rainfall Duration* (Days)	Recorded Rain* (inches)	Estimated Rain** (inches)
1924	October 16-28	Hurricane	BRO	FORT LAU_R	06177	13	23.46	16.74
1985	July 17-23	Tropical Storm Bob	COL	NP-EVC	H1988	7	23.10	n/a
1981	August 15-21	Tropical Storm Dennis	DAD	NP-IFS	HB872	7	20.90	20.38
1933	July 29-August 3	Tropical Storm	PAL	WPB_R	06191	6	19.68	n/a
1904	October 12-20	Hurricane	PAL	JUPITE 3_R	06216	9	19.59	6.03
1960	September 3-12	Hurricane Donna	DAD	PERRINE_R	06167	10	19.16	8.48
1995	August 22-28	Tropical Storm Jerry	CHA	PLANT IN_R	05966	7	18.33	16.18
1999	October 14-17	Hurricane Irene	DAD	S41_R	16675	4	17.47	17.46
1950	October 14-21	Hurricane King	LAK	TITUSVIL_R	06400	8	16.06	14.19
1994	November 13-17	Tropical Storm Gordon	PAL	ANDYTOWN W	16642	5	15.97	16.00
1951	October 1-3	Tropical Storm	LEE	BONITA S_R	06189	3	15.72	15.72
1947	October 8-14	Hurricane	BRO	DANIA 4_R	06178	7	15.65	n/a
1935	September 1-5	Hurricane	DAD	EVERGL 2_R	06161	5	14.51	13.25
1903	September 2-13	Hurricane	PAL	JUPITE 3_R	06216	12	14.08	n/a
1929	September 21- October 2	Hurricane	DAD	COCONUT_R	06168	12	14.00	10.58
1992	August 23-24	Hurricane Andrew	DAD	NP-NE1	H6057	2	13.98	6.90
1933	September 1-7	Hurricane	POL	ST LEO	HK874	7	13.82	n/a
1948	October 4-6	Hurricane	PAL	POMPANO B_R	06179	3	13.33	9.95
1919	September 9-12	Hurricane	MON	KEY WEST_R	06162	4	13.30	n/a
1959	October 16-20	Tropical Storm Judith	PAL	PRATT AN_R	06122	5	13.12	n/a
1979	September 2-3	Hurricane David	IND	VERO TOW_R	06098	2	13.00	8.92
1936	June 15	Tropical Storm	HEN	LA BELLE_R	06158	1	12.47	12.47

1928	August 3-9	Hurricane	POL	JUPITE 3_R	06216	7	12.35	n/a
1928	September 16-21	Hurricane	DAD	MIAMI CI_R	06249	6	12.30	n/a
1932	August 23-30	Tropical Storm	COL	MIAMI CI_R	06249	8	12.09	10.24
1926	September 8-21	Hurricane	LEE	FELLSMER_R	06142	14	11.88	8.02
1948	September 20-23	Hurricane	GLA	BENBOW_R	06128	4	11.87	11.00
1935	November 4	Hurricane	MON	LONG KEY_R	06217	1	11.80	11.80
1987	October 11-12	Hurricane Floyd	STL	LOTELLA_R	05853	2	11.62	5.20
1998	September 21-25	Hurricane Georges	MON	NP-P34	H1998	5	11.52	n/a
1947	September 16-19	Hurricane	HEN	S80_R	06237	4	11.40	8.72
1945	September 14-16	Hurricane	ORA	ORLAN WP_R	06214	3	11.11	n/a
1921	October 23-27	Hurricane	MRN	TITUSVIL_R	06400	5	11.03	n/a
1925	November 30-December 1	Hurricane	DAD	COCONUT_R	06168	2	10.96	15.10
1995	July 30-August 4	Hurricane Erin	BRE	MELBOURN_R	06401	3	10.84	8.81
1964	October 16	Hurricane Isbell	BRO	S13_R	05806	1	10.50	5.09
1988	November 22-24	Tropical Storm Keith	PAS	ST LEO	HK874	3	10.27	11.00
1964	August 24-29	Hurricane Cleo	MAR	STUART 1_R	06187	6	10.19	6.80

* Recorded Rainfall Data from DBHYDRO

** Estimated Rainfall Data from Attaway (1999) and Neumann, et al. (1993)

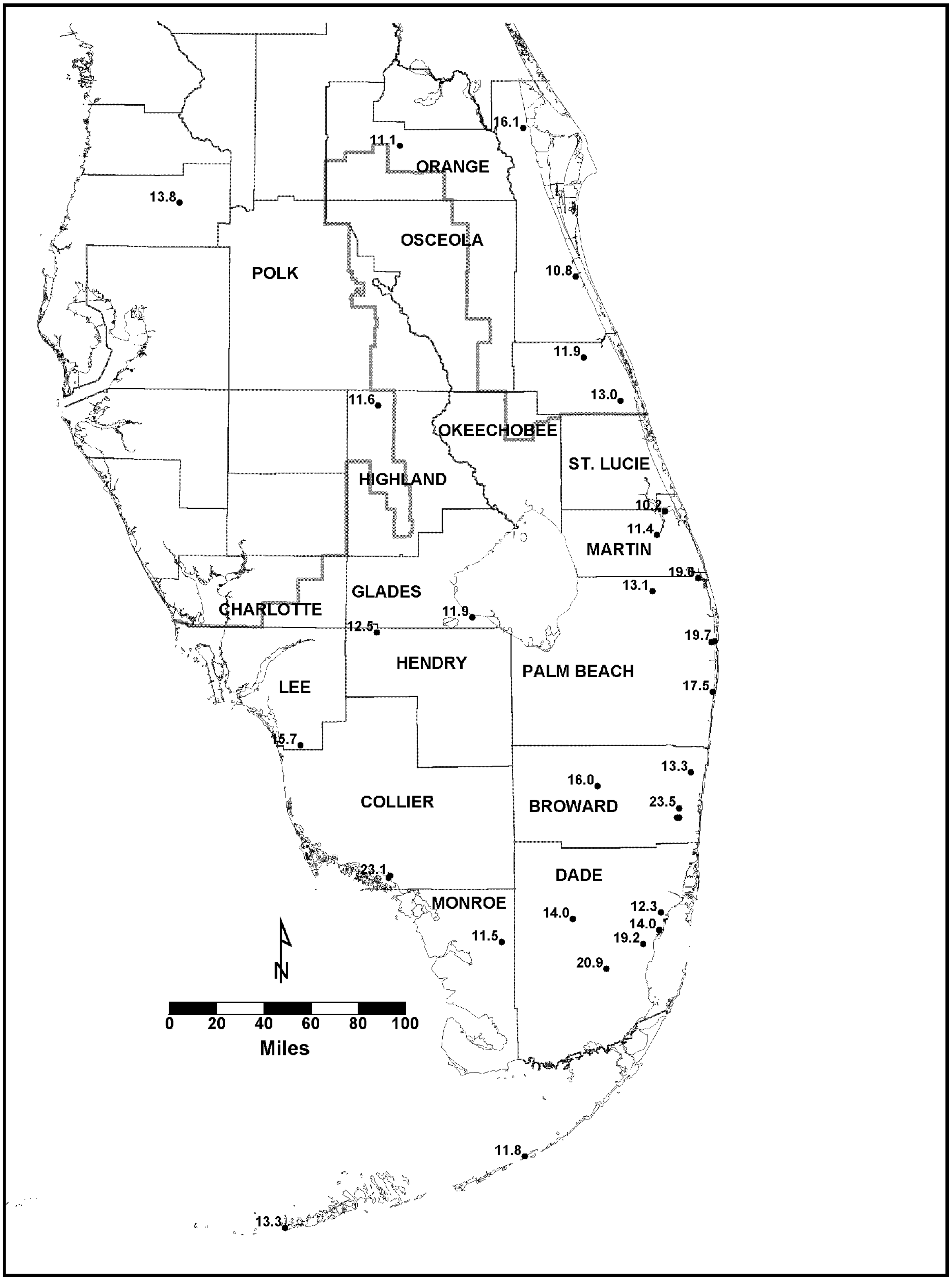


Figure 4. Location of Selected Rain Gages with Maximum Recorded Rainfall From Hurricanes and Tropical Storms During 1900-1999

Appendix G shows the maximum rainfall amount produced in one-day duration from 59 hurricanes and tropical storms in the last 100 years. **Table 8** shows the top 23 events that generated highest rainfall (greater than 9.9 inches) during one-day duration from hurricanes and tropical storms in the last 100 years. The majority of the rainfall data for the one-day durations obtained from the DBHYDRO include "!" or "A" tags, which indicate that the data are questionable or cumulative rainfall from the previous days. However, the daily rainfall data, without tag, indicated that the 14.5 inches of rain fell in Collier County from tropical storm "Bob" on July 23, 1985. In addition, 13.7, 11.2, 10.3 and 9.9 inches of rain from one-day durations were recorded on August 24, 1992, September 25, 1998, August 25, 1995, and October 20, 1924, respectively.

Table 8
23 Highest Rainfall Events of One- day Duration from Hurricanes and Tropical Storms During 1900-1999

Year	Date	Type of Storm	County	Station	Dbkey	Rainfall Date	Rainfall Amount Recorded* (inches)
1951	October 1-3	Tropical Storm	LEE	BONITA S_R	06189	02-Oct-51	15.72!
1985	July 17-23	Tropical Storm Bob	COL	NP-EVC	H1988	23-Jul-85	14.50
1992	August 23-24	Hurricane Andrew	DAD	NP-NE1	H6057	24-Aug-92	13.69
1981	August 15-21	Tropical Storm Dennis	DAD	HOMES.ES_R	06268	17-Aug-81	13.60!
1947	October 8-14	Hurricane	BRO	DANIA 4_R	06178	12-Oct-47	13.04!
1960	September 3-12	Hurricane Donna	DAD	RAILING_R	05811	10-Sep-60	12.66!
1936	June 15	Tropical Storm	HEN	LA BELLE_R	06158	15-Jun-36	12.47!
1933	July 29-August 3	Tropical Storm	PAL	WPB_R	06191	31-Jul-33	12.01!
1935	November 4	Hurricane	MON	LONG KEY_R	06217	04-Nov-35	11.8!
1999	October 14-17	Hurricane Irene	DAD	S331W	16261	15-Oct-99	11.67!
1933	September 1-7	Hurricane	POL	BARTOW_R	06131	05-Sep-33	11.50!
1948	October 4-6	Hurricane	PAL	BOCA_R	06254	05-Oct-48	11.40!
1994	November 13-17	Tropical Storm Gordon	PAL	JUPITER_R	05888	18-Nov-94	11.40A
1998	September 21-25	Hurricane Georges	MON	NP-P34	H1998	25-Sep-98	11.19
1979	September 2-3	Hurricane David	IND	VERO 4W_R	06262	04-Sep-79	10.73!
1964	October 16	Hurricane Isbell	BRO	S13_R	05806	16-Oct-64	10.50!
1904	October 12-20	Hurricane	PAL	JUPITE 3_R	06216	17-Oct-04	10.48!
1947	September 16 -19	Hurricane	HEN	LA BELLE_R	06158	18-Sep-47	10.40!
1995	August 22-28	Tropical Storm Jerry	CHA	PUNTA G4_R	06139	25-Aug-95	10.35
1948	September 20-23	Hurricane	GLA	LIBERTY_R	06197	21-Sep-48	10.25!
1929	September 21-October 2	Hurricane	DAD	COCONUT_R	06168	29-Sep-29	10.04!
1935	September 1-5	Hurricane	DAD	HOMES.ES_R	06211	03-Sep-35	10.04!
1924	October 16-28	Hurricane	LEE	FT MEYER_R	06193	20-Oct-24	9.92

* Recorded Rainfall Data from DBHYDRO

For these events, the average of maximum rainfall and standard deviation were 11.5 and 5.0 inches, respectively. The range of maximum rainfall for 59 events was between 23.5 and 2.0 inches. A frequency analysis was performed. **Figure 5** shows that 15, 10, 10, 22 and 19 percent of the events generated 6, 8, 10, 12 and 14 inches of rain respectively. Further analysis (**Table 9**) indicated that 5, 25, 50, 75 and 85 percent rainfall events produced the maximum rainfall amounts greater than 22.0, 16.0, 13.0, 10.0 and 8.0 inches, respectively.

A comparison between the historical maximum rainfall generated from all the meteorological systems (including hurricanes and tropical storms; frontal (warm/cold) activities; and convective systems) and the highest rainfall produced from hurricanes and tropical storms was performed. As noted in the pervious section, the maximum rainfall varied from four to 18 inches for one-day duration; it varied from six to 20 inches for three-day duration; and it varied from eight to 22 inches for five-day duration. The highest rainfall, from hurricanes and tropical storms, varied from 1 to 15 inches for one-day durations, whereas the highest rainfall ranged between 2 to 24 inches for the varied durations (maximum duration of 14-days). This indicated that the maximum rainfall produced from hurricanes and tropical storms for one-day duration and for the entire-duration of the event were within the similar range as that of the maximum rainfall generated by all the meteorological systems. However, due to hurricane-related complex meteorological phenomenon, potential for the higher rainfall (than the historical maximum of 23.5 inches) from hurricanes and tropical storms remains probable.

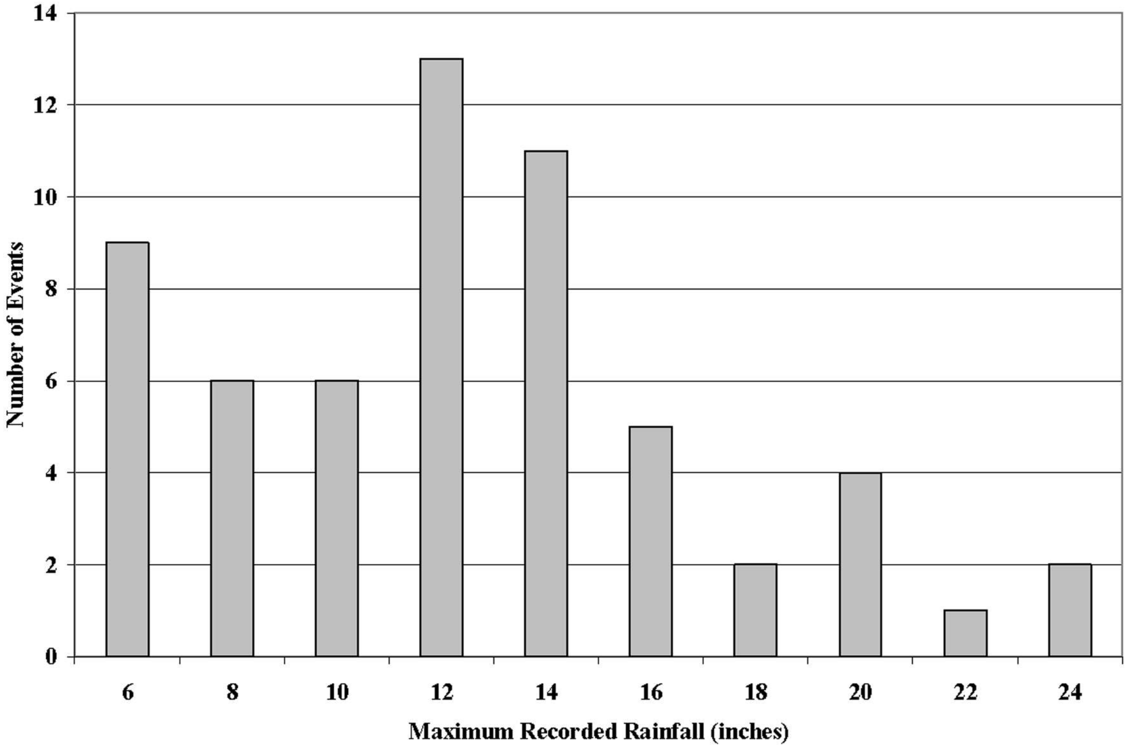


Figure 5. Rainfall Events from Hurricanes and Tropical Storms During 1900-1999

Table 9
Percent of Hurricane and Tropical Storm Events with Maximum Rainfall During 1900-1999

Rainfall (inches) (Equal to or Greater Than)	Hurricane and Tropical Storm Events (percent)
8.0	85
10.0	75
12.0	64
14.0	42
16.0	24
18.0	15
20.0	12
22.0	5
24.0	3

FREQUENCY ANALYSIS OF DAILY RAINFALL MAXIMA

Frequency analysis of hydrologic variables, parameters or data requires that individual observations or data points be independent of each other and that the data be representative of a large and unbiased population (of hydrologic data). This representative data is classified as four types of data: 1) complete duration series, 2) annual series, 3) partial duration series, and 4) extreme value series. For rainfall frequency analysis, annual and partial duration series are often used. The annual series consists of the largest rain amount recorded for the given duration in each calendar year. The size of the data set is equal to the number of years of data available. The partial duration series consists of the same size of series but includes the largest independent events recorded regardless of when they occurred. The partial duration series has higher mean and lower variance than the annual series. In addition, the partial duration series produces higher rainfall estimates for lower return periods. However, Hershfield (1961) found that rainfall estimates for return periods greater than 10 years were same for both the series.

Data Preparation

Several (new and different) data sets were assembled for the frequency analysis of daily rainfall maxima. The following paragraphs provide the details on the data preparation procedures used in creating the required data set for this analysis.

A significantly large portions of the daily rainfall data represent gage readings taken once a day. The time of day when gage readings are taken varies between stations. In some cases, hourly or breakpoint rainfall values are summed over a 24-hour duration to obtain the daily values. Additionally, no effort was expended to estimate maximum rainfall during a 24-hour period from the hourly or breakpoint rainfall measurements. No adjustments were made to the data due to gage type or its exposure. Certain stations have accumulated rainfall totals during weekends, holidays and other days. These stations may have reliable data. However, for daily rainfall records, these accumulated totals were not considered in this study. To consider the accumulated total, the total rainfall needs to be distributed over the individual days during which it was accumulated, based on its temporal distribution at the nearby stations that had daily rainfall record available. This process could have yielded in some additional data that could have increased the size of the data set, however, only marginally. In addition, the daily rainfall data succeeded by a "!" tag were not included in the data set due to their questionable status.

Like previous District studies, this study also did not adjust the daily data to the same 24-hour period and used only daily measured values of rainfall. No attempt was made to estimate missing daily rainfall data for the gage records. The gage records that are located within the Key West islands and Lake Okeechobee were not used in the study.

The following procedure was used in data-set preparation for frequency analysis. First, all gage records with a period-of-record greater than 50 years were selected from all the three regions. In addition, first highest 25 gage records for each region with maximum rainfall amounts were selected. These gage records were obtained for data analysis and are presented in the previous section of this report (also see **Appendices B, C and D**). Then, the selected gage records were grouped into clusters based on their x and y coordinates (i.e., state plane system for geographic location).

Each cluster was developed individually to include all the gage records that were located one to three miles apart from each other. The distance of one to three miles among gage stations was considered appropriate for this purpose, and it was based on the assumption that the spatial variability of the daily rainfall would be low within this distance between the pairs of gages. ArcView software was used to develop these clusters in each region. The clusters had varied numbers of gage records varying from one to eight gage records in each cluster. All the gage records, if available in DBHYDRO, were included in a cluster regardless of their previous selection status. These steps were repeated for all the three regions.

This process of grouping several gage records into clusters was considered appropriate and useful in various ways. These include an increase in the period-of-record, availability of missing data from nearby gage records, combining data for overlapping periods-of record, and reducing (to some extent) spatial variability for shorter distances among the gage records.

In this part of the analysis, annual series values were generated for each calendar year and for each cluster using the gage records and their available daily data records from DBHYDRO. In order to obtain the longest annual series for the calendar year, records from the first year of the gage records to December 31, 1999, where available, were used. However, the clusters with less than five years of data were not considered in the analysis.

Rainfall Duration

In most analyses, the total rainfall amount, for a given short duration, is assumed to occur over the entire period of its duration in a given pattern. Therefore, it is expected that the total rainfall amount for a given duration is developed from breakpoint (or hourly) rainfall recorded data set. The breakpoint (or hourly) rainfall data are available for very small and limited number of gages and for very short period-of-record at the District. However, the daily rainfall data are available from large number of gages and for sufficiently longer period-of-record. Hence, the daily rainfall data were used for this study. Three rainfall durations (i.e., one-day, three-day, and five-day) were used for this analysis. One-day, three-day, and five-day duration rainfall amounts consist of total amounts from 24, 72, and 120 - hour period, respectively. Due to limitations cited above, one-day duration rainfall is considered equal to non-zero daily rainfall amounts and assumed to have occurred over 24-hour period. Similarly, non-zero daily rainfall amounts from three and five consecutive days are considered as three-day and five-day duration, respectively.

The rainfall data for the selected gage records used in each cluster were available from DBHYDRO. All the data for the selected gage records represent daily rainfall data. The non-zero daily rainfall values were considered as one-day duration rainfall amounts and were used for generating the annual series as explained above.

Three-day duration rainfall data were constructed by accumulating three consecutive days of non-zero daily rainfall values for each year. A set of SQL statements was used to obtain a value of maximum rainfall amount (of three-day duration) for each year and for all the years within the period-of-record. These steps were repeated for all the gage records. This annual three-day rainfall data were used in generating annual series for each cluster using the procedure described above.

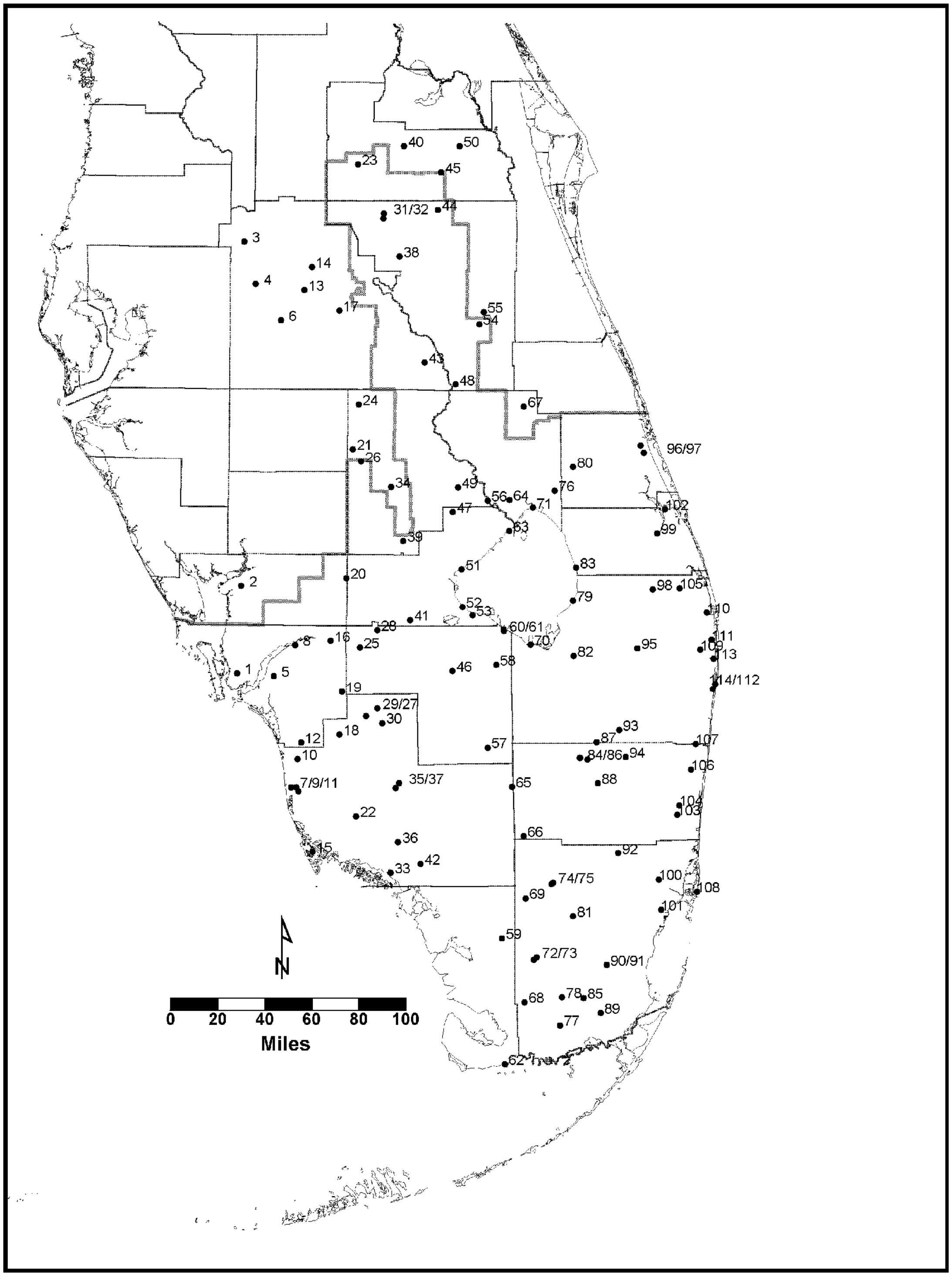
Five-day duration rainfall data were constructed by accumulating five consecutive days of non-zero daily rainfall values for each year. A set of computer programs (SQL statements) was used to obtain a value of maximum rainfall amount (of five-day durations) for each year and for all the years within period-of-record. Subsequently, these steps were repeated for all the gage records. This annual five-day rainfall data were used in generating annual series for each cluster using the procedure as described above.

Table 10 shows the number of clusters developed for north, east and west regions and for one-day, three-day and five-day durations. Subsequently, each cluster was identified by one unique dbkey representing one gage station. The information on each cluster is presented in **Appendices H, I** and **J** for one-day, three-day and five-day duration respectively.

Table 10
Number of Clusters Developed for Three Regions and Three Durations

Regions	One-Day	Three-Day	Five-Day
North	23	20	22
East	35	34	25
West	28	13	19
TOTAL	86	67	66

The spatial location of the selected rain gage stations (i.e., each cluster is representing one gage station) used in this study is shown in **Figures 6A and 6B**. The rain gage numbers are shown on the District Map in **Figure 6A**. The station identification and their respective dbkeys of these rain gages numbers are presented in **Figure 6B**.



NOTE: Station Identification for the Rain Gage Numbers are presented in Figure 6B.

Figure 6A. Location of the Selected Rain Gages on the District Map

Rain Gage No.	STATION	DBKEY	Rain Gage No.	STATION	DBKEY
1	CAPECOR1_R	05900	58	L1 RANCH_R	06279
2	PUNTA G4_R	06139	59	NP-P34	H1998
3	PROVIDEN_R	06395	60	HGS2_R	06240
4	LAKELA 5_R	06130	61	CLEW_R	06188
5	FT MEYER_R	06193	62	NP-FLA	H6054
6	BARTOW_R	06131	63	A127_R	16220
7	NAPLES_R	06160	64	G80_R	12777
8	SLEE_R	06081	65	C-54_R	05668
9	GOLD.W1_R	00838	66	3A-SW_R	JA344
10	COCOH.WB_R	00843	67	FORT DRU_R	06232
11	NAPLES T_R	06090	68	NP-P38	06039
12	BONITA S_R	06189	69	NP-FMB	H2005
13	WINTERHA_R	06132	70	S3_R	06227
14	L ALF EX_R	06133	71	HGS6_R	06153
15	MARCO FI_R	05974	72	NP-P36	06038
16	ALVA FAR_R	05922	73	NP-204_R	00763
17	MOUNTIN_R	06134	74	3A-28_R	00623
18	CORKISL	DJ232	75	COOPER_R	16707
19	CORK.TOW_R	06078	76	DAVIE2_R	16192
20	WHIDDEN3_R	15465	77	NP-P37	H2001
21	BASS 3_R	05658	78	NP-RCR	H6058
22	SITE3_R	01826	79	HGS5X_R	06242
23	ISLEWORT_R	06144	80	COW CREE_R	JG320
24	AVON PRK_R	06136	81	NP-NE1	H6057
25	CONGE 6_R	05931	82	BELLE GL_R	06207
26	DESOTO C_R	06137	83	S308_R	06239
27	L TRAFFO_R	00826	84	3A-NE_R	05864
28	LA BELLE_R	06158	85	NP-RPL	H2004
29	IMMOKA 3_R	06195	86	GAGE1 2_R	02158
30	IMMOKA 2_R	06082	87	S7_R	16652
31	KISS 2_R	06147	88	ANDYTOWN W	16642
32	KISS_R	06146	89	S18C_R	16659
33	NP-EVC	H1988	90	NP-IFS	HB872
34	L PLACI2_R	06150	91	HOMES.ES_R	06211
35	FAKAHATC_R	06022	92	PENNSUCO_R	06253
36	BARRON_R	00808	93	2A-159_R	02325
35	MILES CI_R	06087	94	2A-111_R	00443
38	S61_R	05868	95	S5A_R	05895
39	VENUS 4S_R	06238	96	FORT PIE_R	06151
40	ORLAN AP_R	06185	97	FT PIERC_R	06116
41	S78_R	06243	98	PRATT AN_R	06122
42	TAMIAMI_R	00584	99	S80_R	06237
43	GAC_R	05878	100	HIALEAH_R	06175
44	L MYRTL_R	06278	101	MIAMI CI_R	06249
45	BEELINE_R	05963	102	STUART 1_R	06187
46	DEVILS_R	06079	103	S13_R	05806
47	S75_R	16663	104	FORT LAU_R	06177
48	ARMSSO_R	05750	105	SIRG	15730
49	LYKEF_R	05741	106	POMPANOB_R	06179
50	BITHLO_R	06199	107	G56_R	05842
51	S131_R	06120	108	MIAMI BE_R	06172
52	HGS1_R	06124	109	WPB AIRP_R	06182
53	BENBOW_R	06128	110	S44_R	16674
54	KENANS1_R	06867	111	PLANT IN_R	05966
55	NITTAW 1_R	06140	112	S41_R	16675
56	OKEE 9W_R	06152	113	S155_R	16583
57	BIG CY_R	06190	114	HYPOLUXO_R	06180

Figure 6B. Stations of the Selected Rain Gages Located Within the District

Methodology

All the gage stations (i.e., each gage station is representing one cluster) were selected for frequency analysis of daily rainfall maxima. The rainfall annual series data for three different durations and the stations were fitted with several standard probability distributions. To determine the best-fitted probability distribution, a set of criteria was established. Four criteria were developed to obtain the best-fit probability distribution. Based on the criteria for the best fit, a probability distribution was selected. This selected probability distribution was used to fit the annual series data for all the selected stations. The results of the analysis provided the rainfall depths for various return periods at each station. These processes were repeated for three rainfall durations (i.e., one-day, three-day, and five-day).

Probability Distributions Applied

In the literature, several probability distributions are used for rainfall frequency analysis. The most commonly used distributions are Gumbel distribution (also known as Fisher-Tippet Type I distribution), Normal distribution, two-parameter Log Normal distribution, three-parameter Log Normal distribution, two-parameter Gamma distribution, three-parameter Gamma distribution, Weibull distribution, and Log Pearson Type III distribution. The mathematical details on the above mentioned probability distributions can be found in any statistical related text or reference books (e.g., Haan, 1977).

For this study, seven probability distributions were considered. The distributions were Normal, two-parameter Log Normal, three-parameter Log Normal, two-parameter Gamma, three-parameter Gamma, Weibull and Log Pearson Type III. A frequency analysis computer program by Hosung Ahn (Fortran computer program developed to select parameters for various probability distributions suited for frequency analysis, SFWMD, 1990) was used. Based on the available period-of-record for each station, the annual series were generated and used by the computer program.

Selection Criteria for Best-Fit Probability Distribution

When several probability distributions are fitted to a given data series, a set of criteria is required to test the goodness of fit. There are two statistical tests available for determining the goodness of fit and they are 1) Chi-Square test and 2) Kolmogorov-Smirnov test. In both, the hypothesis is tested that the given data series are from a specific probability distribution.

It has been found (Haan, 1977) that neither test is very powerful. When these tests are used, the probability of accepting the hypothesis is very high when it is in fact false. In addition, these statistical tests are insensitive to the tails of the probability distributions. However, the sensitivity of chi-square test can be improved in the tails of the distribution if classes are not combined to get an expected frequency (for the last classes) of 3 to 5. The drawback of this is that a single observation in a class with a low expectation can result in a higher than critical value of chi-square, in turn rejecting the hypothesis. No alternate tests are available to test the goodness of fit.

For this study, a chi-square test was used to test the goodness of fit for the seven selected probability distributions. The computer program computed the chi-square value for each distribution at each selected station. The probability distribution, which accepted the test hypothesis (with the chi-square value lower than the tabulated value), was considered further for the best-fitted distribution for that station and for the given duration.

Haan (1977) states that in choosing a distribution for frequency analysis one may be tempted to select a distribution with a large number of parameters. Generally, the more parameters a distribution has, the better it will adapt to a set of data series. However, for the sample size (most often between 30 to 50) available in hydrology, the reliability in estimating more than two or three parameters may be quite low. Thus, a compromise must be made between flexibility of the distribution and reliability of the parameters. Fiering and Jackson (1971) provided a detailed procedure on selecting a probability distribution. They stated that the statistical tests available for testing the goodness of fit of theoretical distributions to a set of large data series can not alone aid in the choice of a distribution. The selection of a distribution must involve some intuition and common sense as well.

In order to determine the best-fitted probability distribution for the selected gage stations, four criteria were used:

a. lowest total (cumulative) chi-square value for the selected stations,
b. maximum number of stations that have lowest chi-square value, and
c. least number of stations that have rejected the hypothesis.
d. Minimum difference between the maximum recorded rainfall amount (used in the annual series) and 100-year rainfall estimate by the selected distribution.

Selection of a Probability Distribution for Analysis

Wanielista et al. (1996) fitted six probability distributions to rainfall data at 25 sites in Florida. They reported that the two-parameter Log Normal and the Log Pearson Type III distributions gave the best fit for the rainfall data for various durations. Two previous similar studies (Trimble, 1990 and MacVicar, 1981) at the District used Gumbel distribution. It was noted (Trimble, 1990) that the Gumbel distribution is essentially a two-parameter Log Normal distribution with constant skewness. These findings were similar to the one found above in this study.

MacVicar (1981) stated that although statistical tests can give a valuable insight into the consequences or the validity of certain assumptions, they are often inconclusive. In selecting a probability distribution for frequency analysis, factors other than the technical questions must also be considered. Some of these include general acceptance by practicing professionals, results of other similar research work, and an established precedent in using the selected procedure as a design standard.

The annual series data sets from the selected gage stations for each duration were fitted with seven probability distributions. In most cases, the Normal and Weibull probability distributions did not fit adequately well. This was evident from computed chi-square values for these distributions, which were higher than the tabulated chi-square values. However, in most cases, the other five distributions namely, two-parameter Log Normal, three-parameter Log Normal, two-parameter Gamma, three-parameter Gamma, and Log Pearson Type III, fitted reasonably well. It was indicated by the fact that the chi-square test hypothesis was accepted often for these five probability distributions. The results of chi-square tests are presented in **Appendices K,** L, and **M** for one-day, three-day, and five-day durations respectively.

Furthermore, review of results reveals that the computed chi-square values for the five probability distributions at each station are close to each other in most cases. In addition, in most cases, the computed chi-square values were lower than the tabulated chi-square values. These values indicate level of goodness of fit. In order to determine the best-fit probability distribution, the four selection criteria (as set-forth in the above section) were used.

Based on first three criteria previously established, the probability distributions were evaluated for the three durations. The Log-Pearson Type III, three-parameter Log Normal, and three-parameter Log Normal distributions were most often fitted distributions for one-day, three-day, and five-day durations respectively. No single probability distribution was common among all the three rainfall durations. However, three-parameter Log Normal distribution was common for three-day and five-day durations.

Finally, the fourth selection criterion was used in selecting a probability distribution from the distributions for which the chi-square test hypothesis was accepted for each station and duration. This selection was made such that the 100-year rainfall estimate from the selected distribution and the maximum rainfall amount (at that station) were close to each other. However, in very few cases where none of the considered distributions accepted the chi-square test hypothesis, the fourth criterion and evaluation of the rainfall estimates (by the distributions) were used for selecting the probability distribution.

Quantification of (distribution's) parameter reliability (Bridges and Haan, 1972) and errors in rainfall estimates at various probability levels (or return periods) were not computed. That quantification would require further investigation and it is out of scope for this study.

Results and Discussion

From the selected probability distribution, the rainfall estimates at various probability levels (i.e., inverse of return periods) were determined for each station. The rainfall estimates for two-, five-, 10-, 25-, 50-, and 100-year return periods and for three durations are presented in **Appendices N, O**, and **P.**

The summary of results from the frequency analysis is presented in **Table 11**. The table shows the range of rainfall estimates (in inches) for six return periods and three durations. For 2-year return period, the ratios of three-day to one-day rainfall estimate were 1.31 and 1.32 for minimum and maximum, respectively. For 100-year return period, the ratios of three-day to one-day rainfall estimate were 1.48 and 1.09 for minimum and maximum, respectively. Likewise, for 2-year return period, the ratios of five-day to one-day rainfall estimate were 1.42 and 1.38 for minimum and maximum, respectively. For 100-year return period, the ratios of five-day to one-day rainfall estimate were 1.83 and 1.27 for minimum and maximum, respectively. In addition, it was evident that the rainfall estimated values for a given return period and duration vary from one gage station to another indicating spatial variation in rainfall estimates. As expected, the variations in rainfall estimates for one-day duration are highest compare to three-day and five-day durations. Similarly, the variations in rainfall estimates increase as the return period increase from 2-year to 100-year.

Table 11
Rainfall Estimates (inches) for Various Return Periods and Three Durations

Duration	One-Day		Three-Day		Five-Day	
Return Period	Rainfall (inches)		Rainfall (inches)		Rainfall (inches)	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
2-year	2.6	5.0	3.4	6.6	3.7	6.9
5-year	3.7	8.8	4.9	8.9	5.7	10.0
10-year	4.5	11.4	6.2	11.5	7.1	12.4
25-year	5.3	15.1	7.2	15.4	8.9	16.6
50-year	5.7	17.8	8.1	18.9	10.1	21.2
100-year	6.0	21.0	8.9	22.8	11.0	26.6

The areas located within the Key West islands and Lake Okeechobee were excluded from this rainfall frequency analysis.

SPATIAL CHARACTERISTICS OF DAILY RAINFALL MAXIMA

Spatial variability of the rainfall is a very important component of water resources management. The rainfall characteristics over the Lake Okeechobee and the surrounding ocean are different from that of overland mass. The eastern coast areas receive higher rainfall amounts than western coast areas. The middle areas of Central and South Florida receive less rainfall than coastal areas.

In South and Central Florida, the spatial variations of the individual rainfall events are very high. Specifically, intense short duration rainfall storms have been registering very high spatial variability. At the current level of density of the rain gages within the District, it is not appropriate to perform a meaningful spatial variability analysis for short duration rainfall events. This is due to fact that the daily variograms were found to be pure nuggets (Van Lent and Tracy, 1994). Furthermore, Van Lent and Tracy (1994) reported that the rain gage network was unable to detect any difference between the spatial distribution of daily rainfall and white noise. However, when the point rainfall data are cumulated over a period of a month, season or year, the rainfall amounts correlate well with the neighboring gagged rainfall data and provide a definable spatial variation. These spatial variations are characterized by variogram analyses and have been reported by many researchers (Ali et al., 1999; Moss, 1996; and Van Lent and Tracy, 1994).

One-day, three-day, and five-day duration rainfall storms have very high spatial variability. However, when the point rainfall data are cumulated over a period of a month, season or year, the rainfall amounts correlate well with the neighboring gagged rainfall data. In this study, the semi-variogram analysis of the rainfall estimates did not provide any mathematical model indicating systematic trends or patterns. Due to this large spatial variability, the fitted semi-variogram models were not used in mapping. However, the Kriging method was used to map isohyetal contours.

Spatial Mapping

Uniformly spaced grid data are needed to generate contour maps. In order to generate a regularly spaced grid, a gridding procedure is used. It uses randomly spaced data and applies one of the interpolation methods. There are many methods available for interpolation. Some of the common methods used are inverse distance, minimum curvature and Kriging.

Several publications provide detail information on the Kriging method (e.g., Wanielista et al., 1996; Ali et al., 1999). The Kriging method estimates a value by using nearby known values and a semi-variogram and then minimizes the variance of the estimation error with respect to a weighting factor (as applied to the nearby points). A semi-variogram is a plot of one-half of the expected value of the squared difference between two points with separation distance h. The Kriging method is applied after the semi-variogram has been developed.

This method assumes the best estimate is a weighted average of one or more sample points. The objective function for optimization is to minimize the error variance. The optimal values of the weights are determined by the optimization procedure. The optimization procedure is performed by differentiating with respect to the unknowns and setting each first-order derivative equal to zero. These results, obtained from the procedure, provide the weights for the sample points. These weights are multiplied by their sample point values respectively. These values are then summed to estimate the unknown value.

The number of nearby points used by this estimation method could be fixed or variable. Generally, the greater the number of nearby points used, the better smoothing effect it will have on the variability of the data. Wanielista et al. (1996) used the nearest 10 points to ensure a smooth transition from one area to next while reducing the impact of outlying points for spatial mapping. For this application, the nearby data points are at irregularly spaced intervals. Therefore, more nearby data points for interpolation of values were required.

Point frequency analysis of the temporal distribution of rainfall maxima were performed and reported in the previous section of this report. The selected probability distribution, based on the established best-fit criteria, was applied to fit the annual series data of the each of the selected stations. The results of the application provided the rainfall depths for various return periods at each station. This application was used for all the three rainfall durations (i.e., one-day, three-day, and five-day). Several maps showing (isohyetal) contours of rainfall depths for various return periods and durations were prepared. In addition, three maps showing (isohyetal) contours of rainfall depths for maximum recorded rainfall (the data were obtained from previous section titled "Data Analysis of Maximum Recorded Rainfall") and for each duration were prepared. The Kriging module in Surfer (version 7.03 – August 2000) software package was used. Specifically, the Ordinary Kriging (with assuming a linear model) method was used in mapping the isohyetal contours.

Mapping Results

The **Figures 7, 8, 9, 10, 11, 12** and **13** show isohyetal maps for two-, five-, 10-, 25-, 50- and 100- year return periods and maximum recorded for one-day duration rainfall.

The **Figures 14, 15, 16, 17, 18, 19** and **20** show isohyetal maps for two-, five-, 10-, 25-, 50-, and 100- year return periods and maximum recorded for three-day duration rainfall.

The **Figures 21, 22, 23, 24, 25, 26** and **27** show isohyetal maps for two-, five-, 10-, 25-, 50-, and 100- year return periods and maximum recorded for five-day duration rainfall.

The areas located within the Key West islands and Lake Okeechobee were excluded from mapping the isohyetal contours.

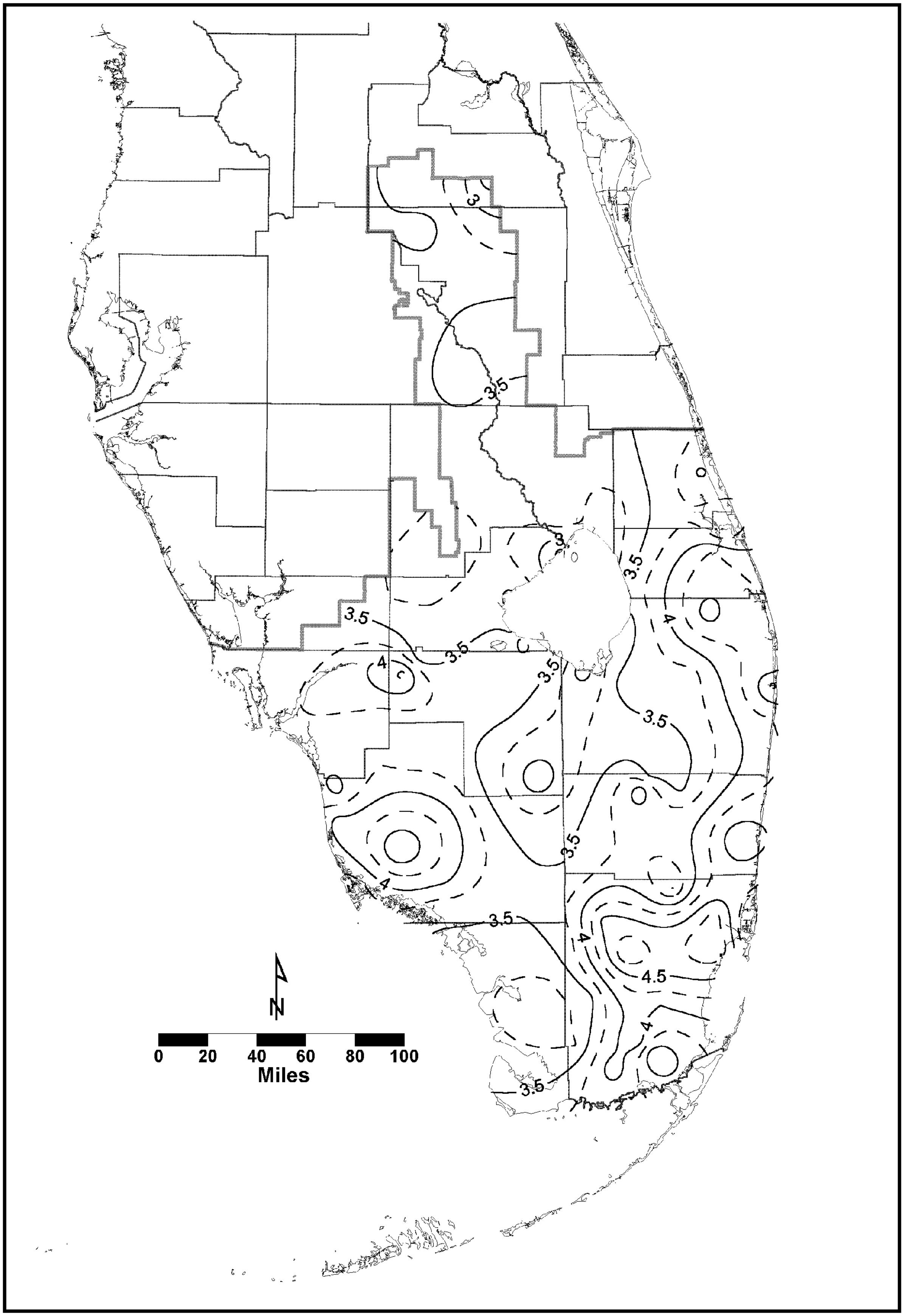


Figure 7. One - Day Maximum Rainfall (in inches): 2-Year Return Period

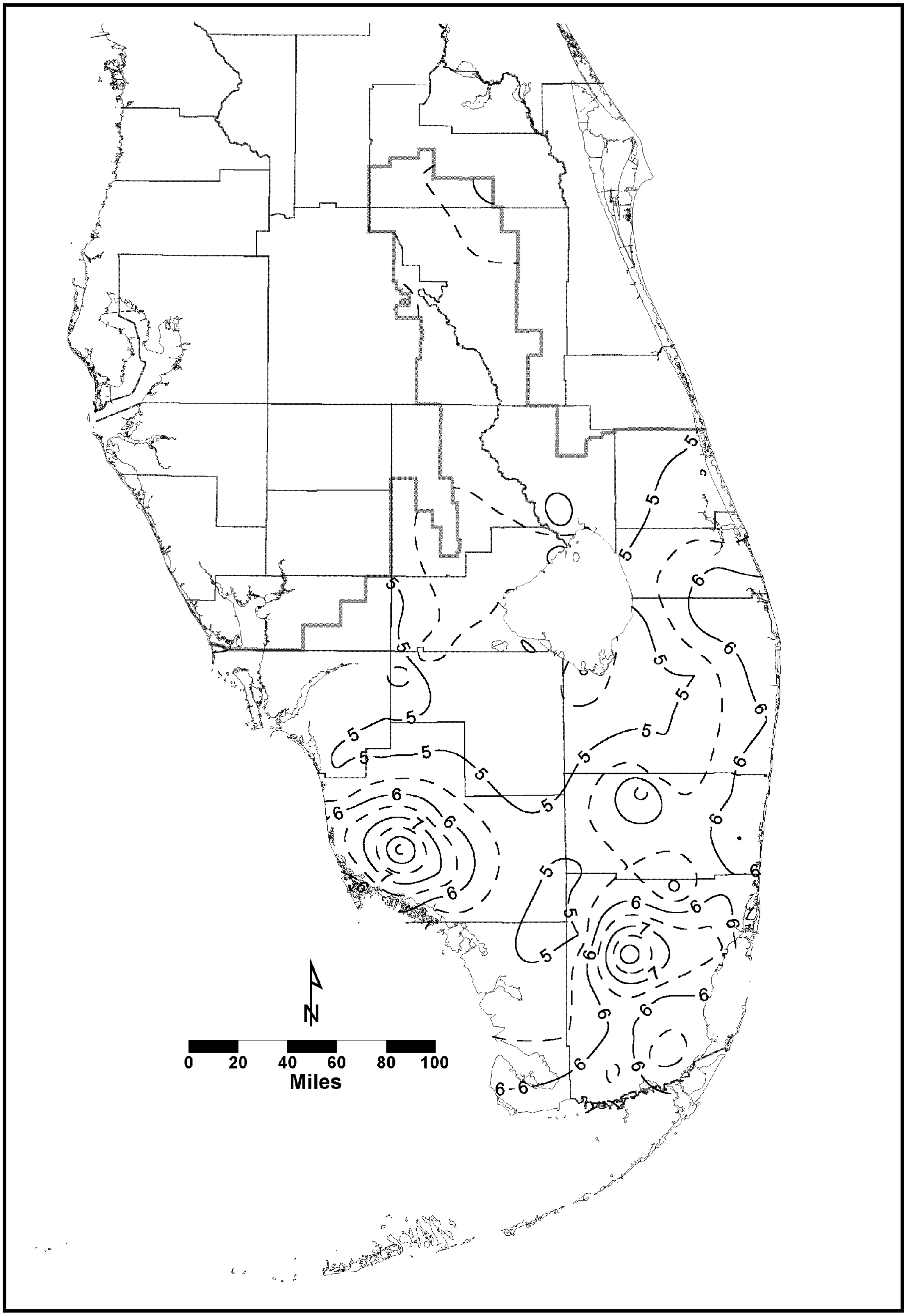


Figure 8. One - Day Maximum Rainfall (in inches): 5-Year Return Period

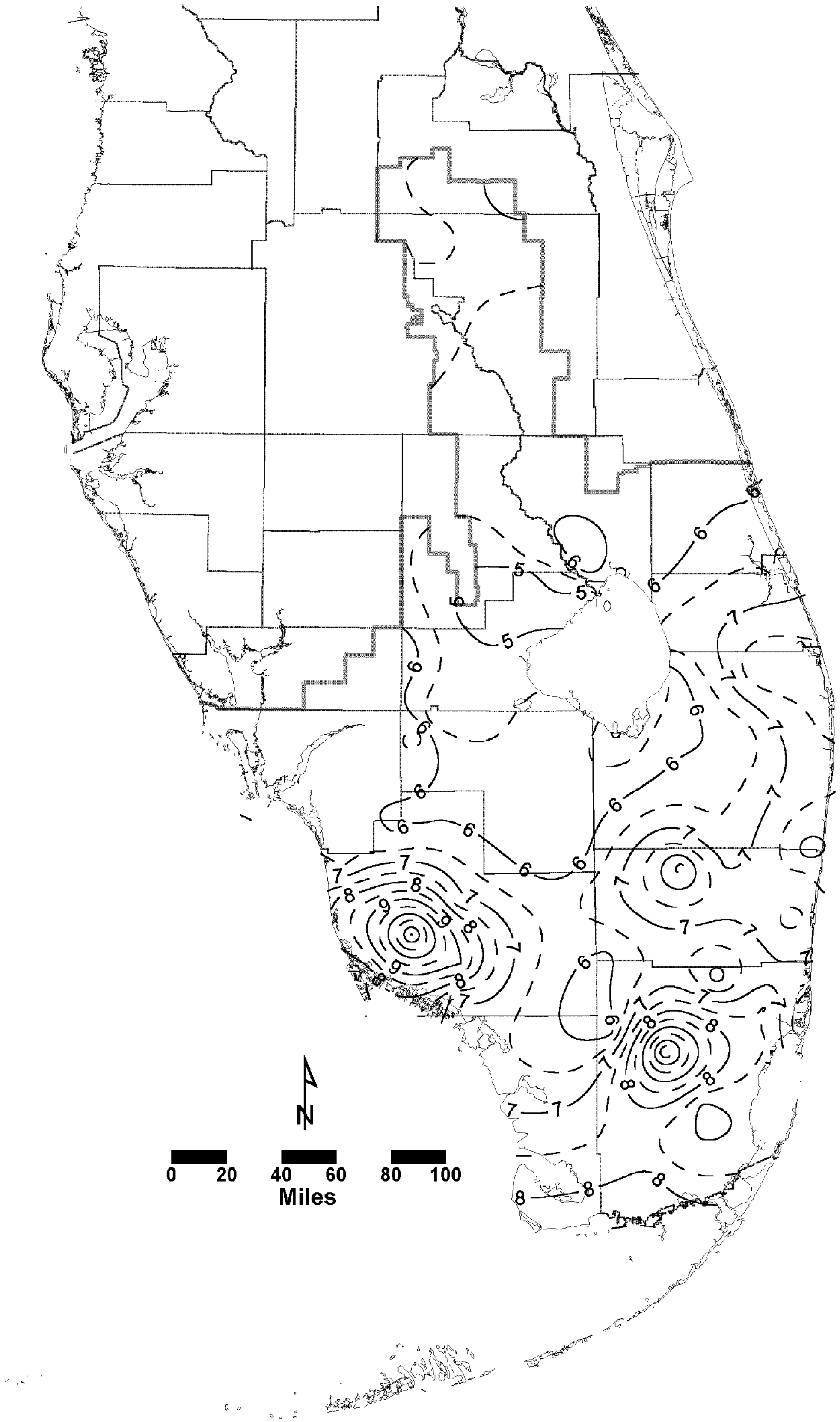


Figure 9. One - Day Maximum Rainfall (in inches): 10-Year Return Period

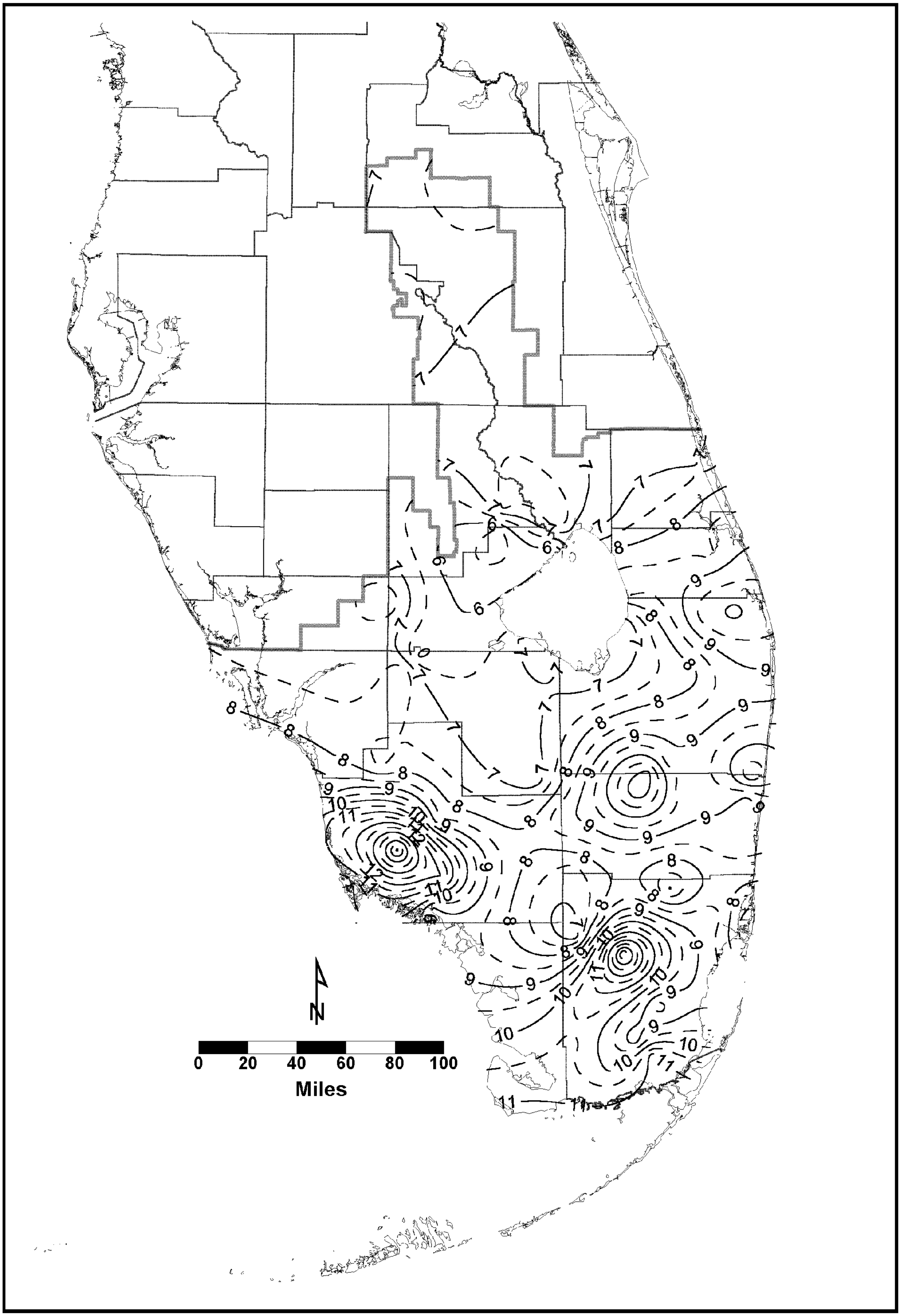


Figure 10. One - Day Maximum Rainfall (in inches): 25-Year Return Period

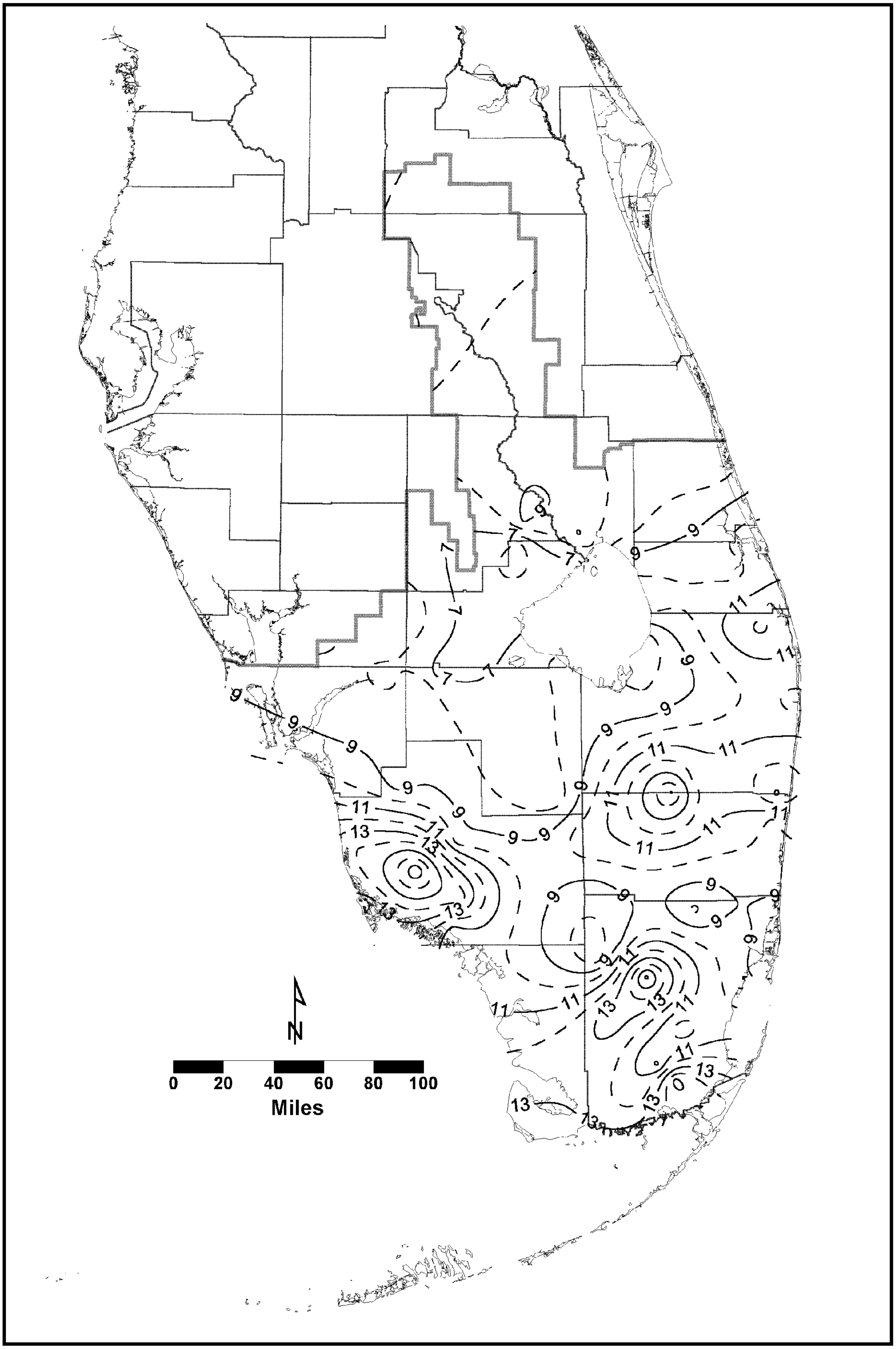


Figure 11. One - Day Maximum Rainfall (in inches): 50-Year Return Period

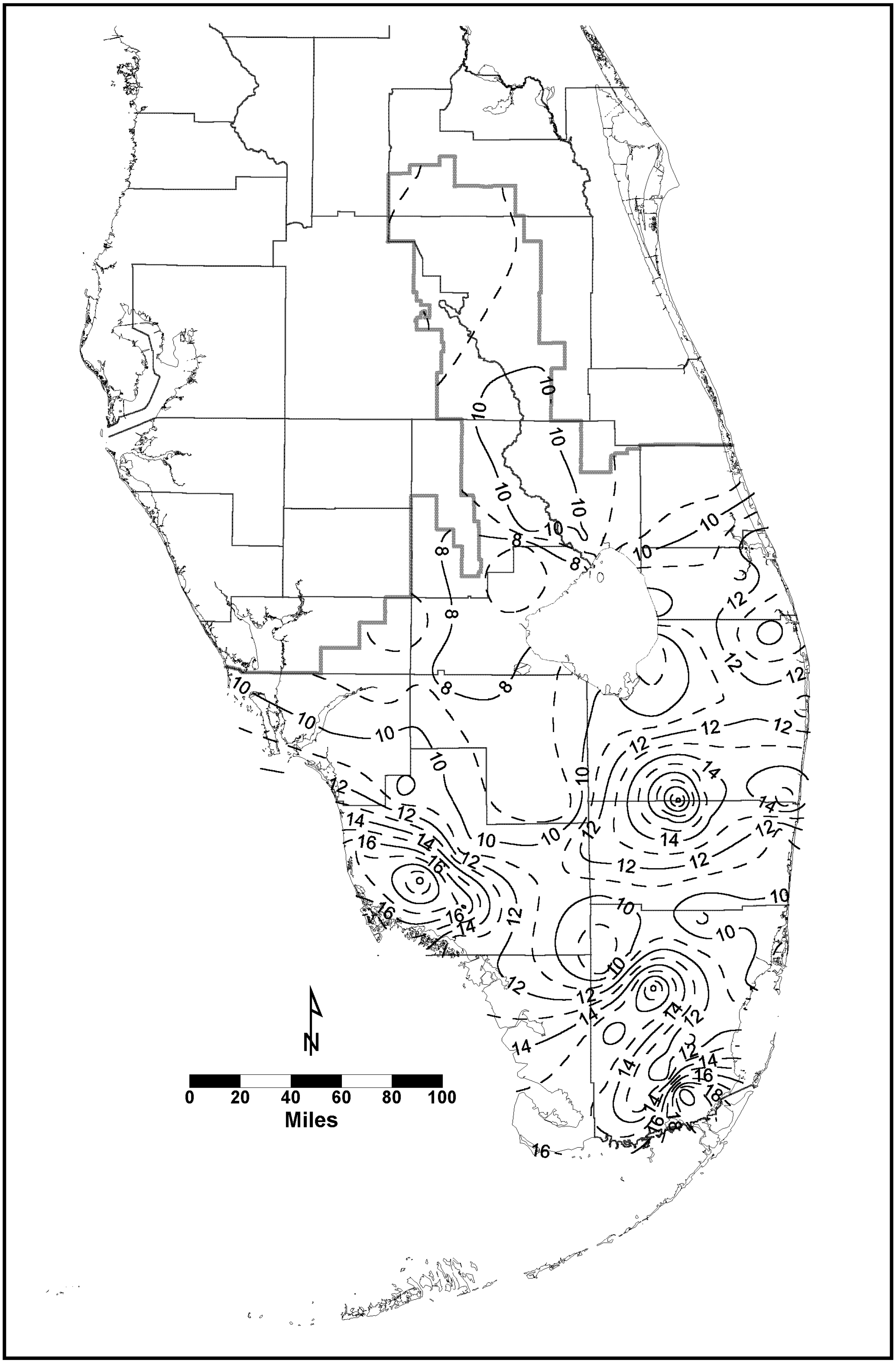


Figure 12. One - Day Maximum Rainfall (in inches): 100-Year Return Period

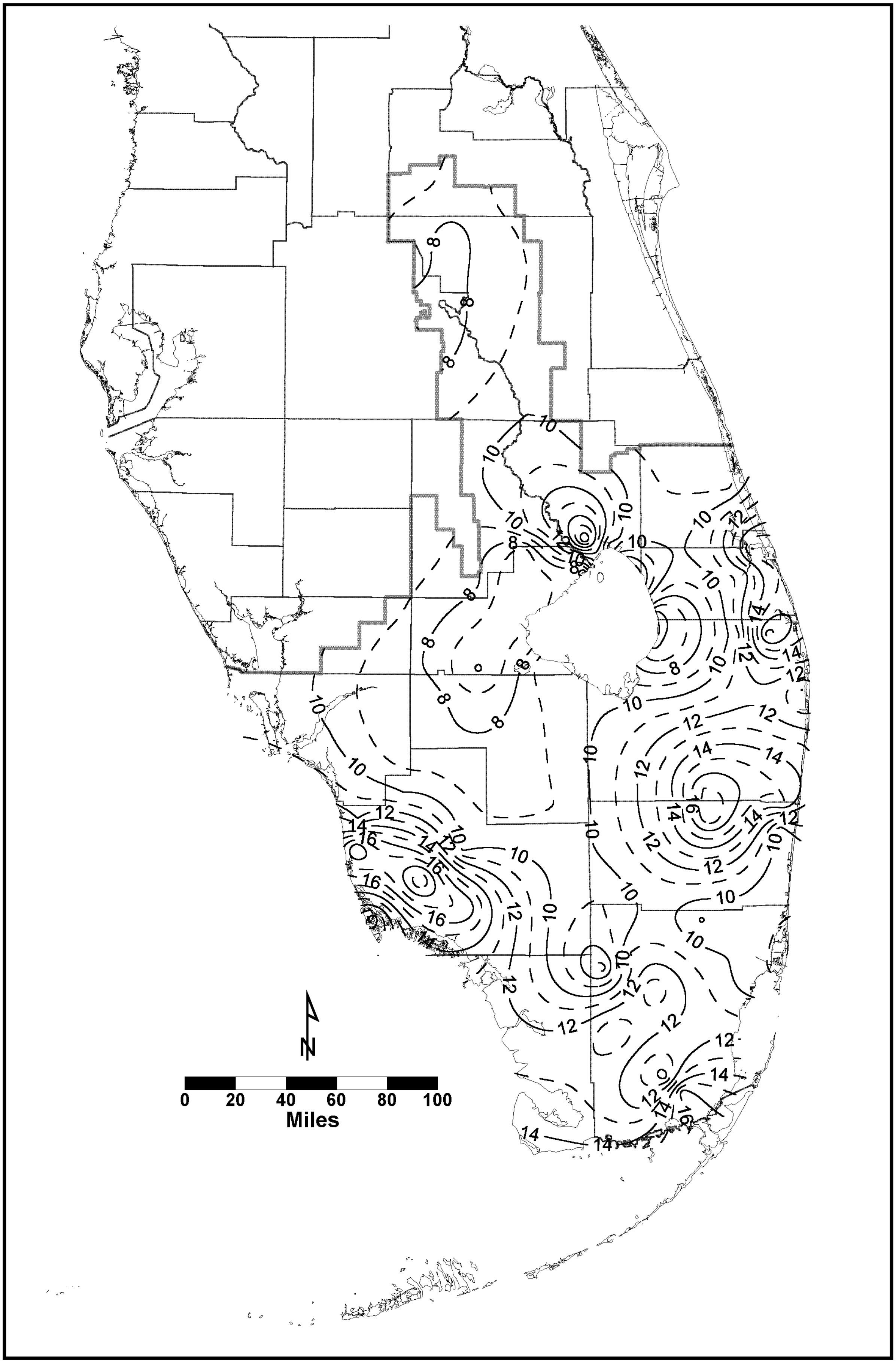


Figure 13. One - Day Maximum Rainfall (in inches): Maximum Recorded

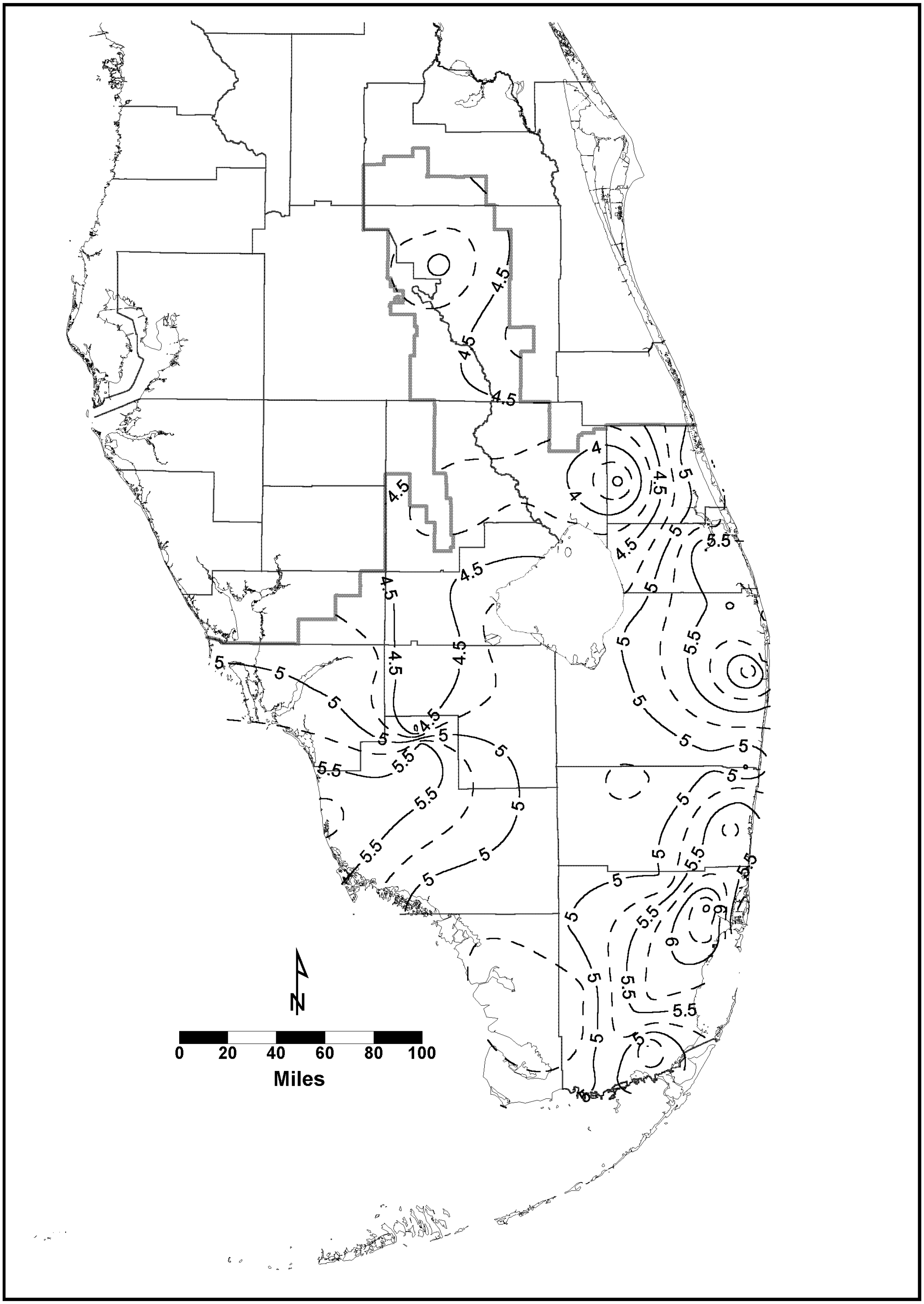


Figure 14. Three - Day Maximum Rainfall (in inches): 2-Year Return Period

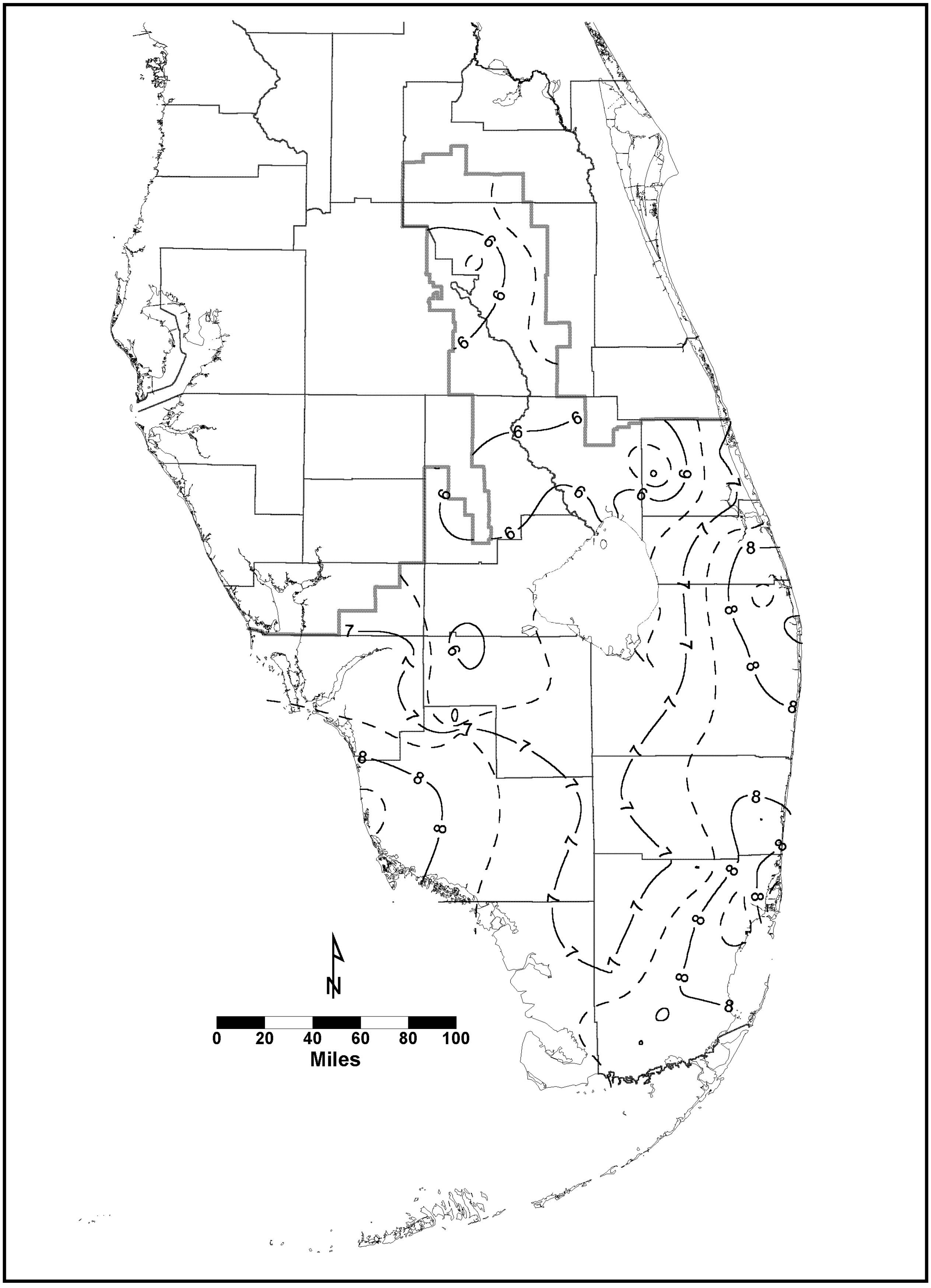


Figure 15. Three - Day Maximum Rainfall (in inches): 5-Year Return Period

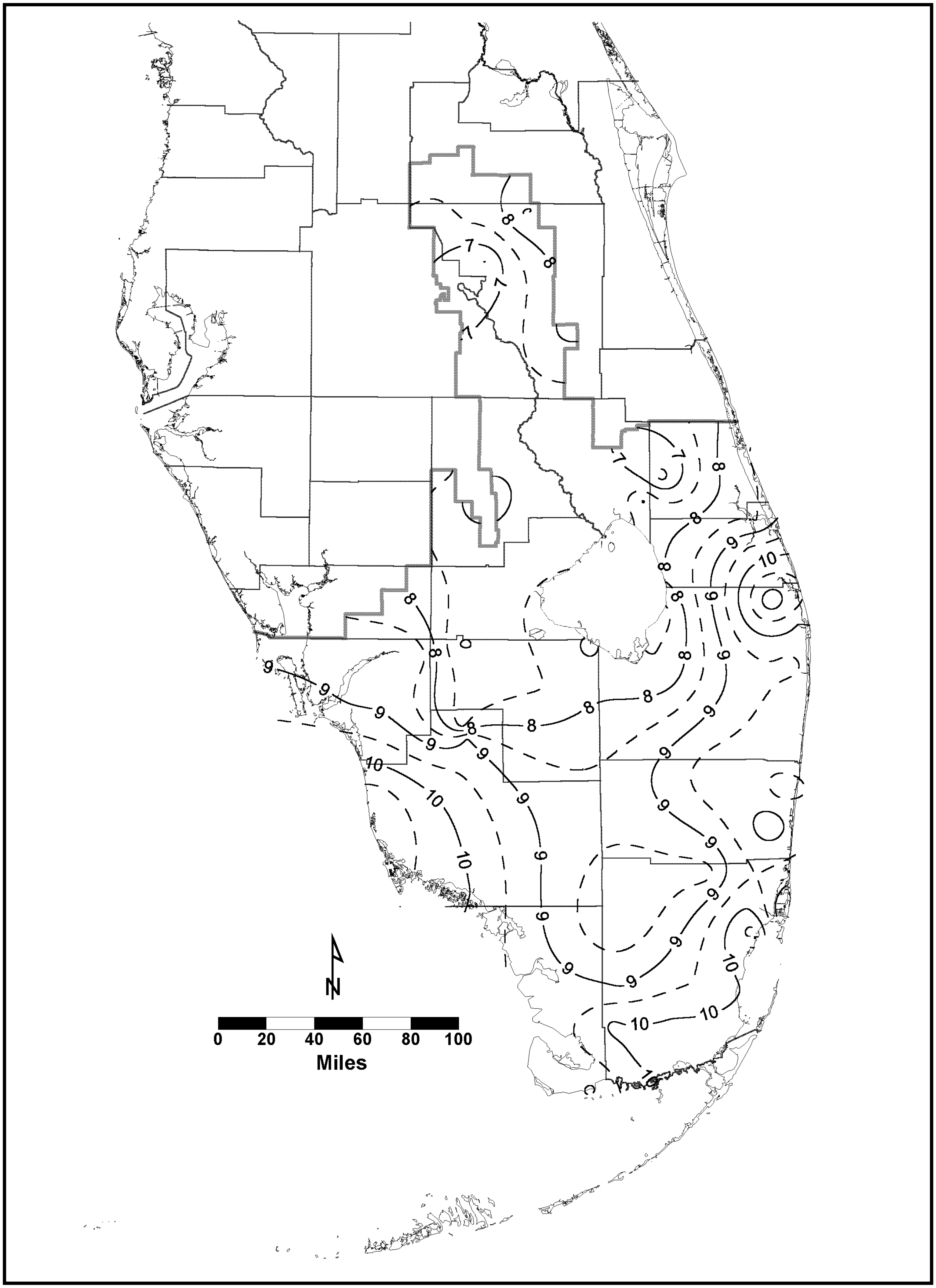


Figure 16. Three - Day Maximum Rainfall (in inches): 10-Year Return Period

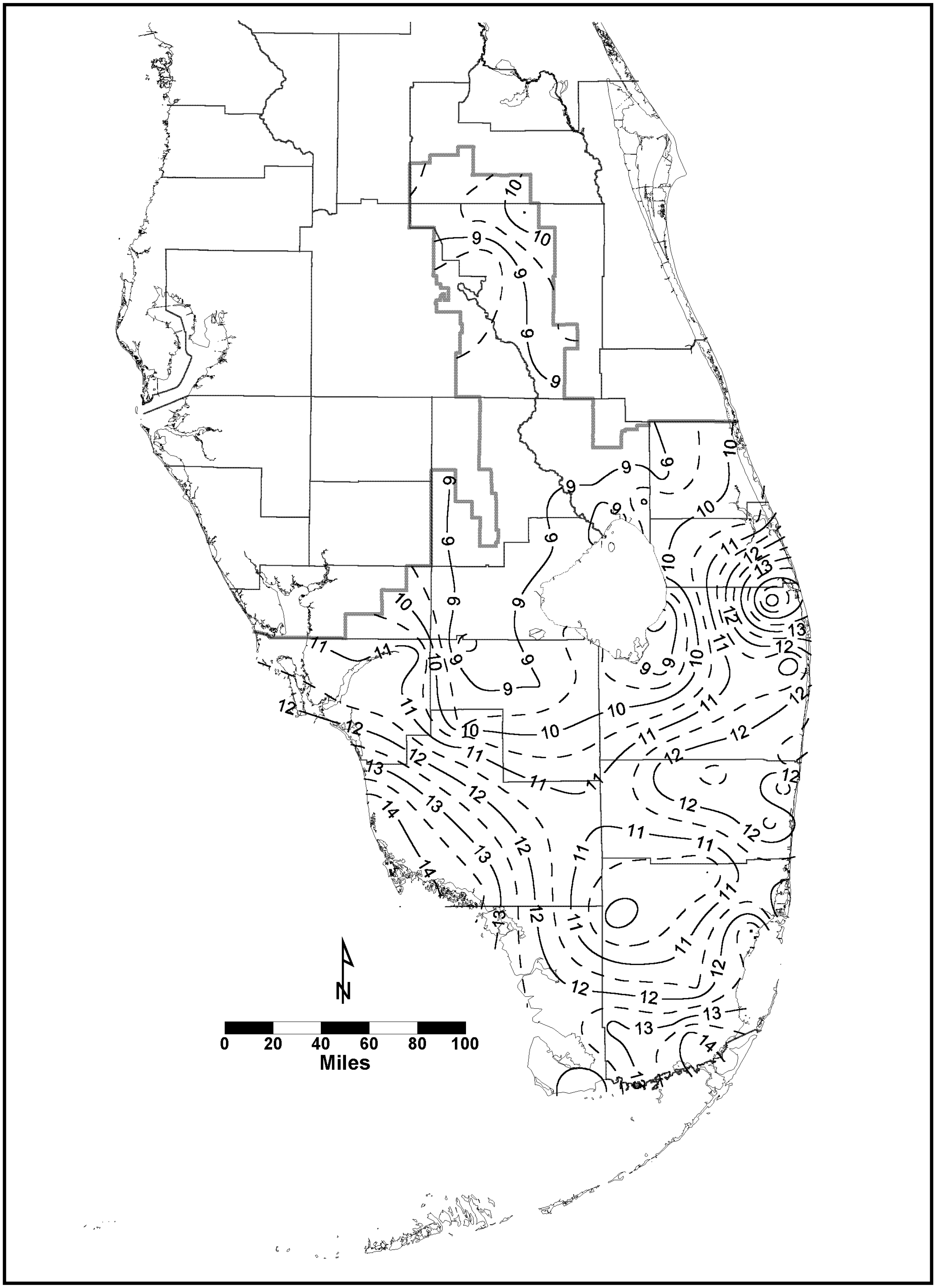


Figure 17. Three - Day Maximum Rainfall (in inches): 25-Year Return Period

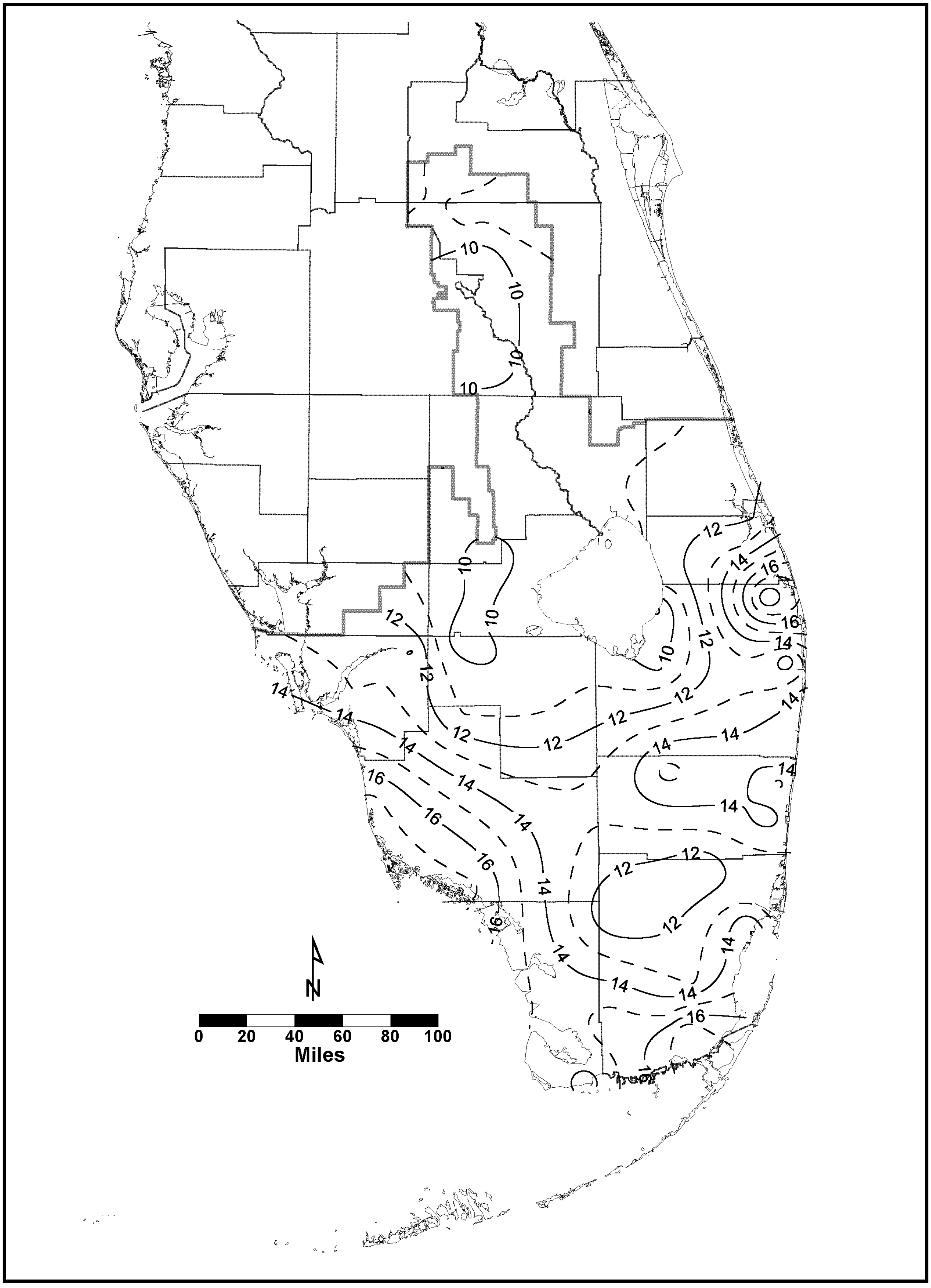


Figure 18. Three - Day Maximum Rainfall (in inches): 50-Year Return Period

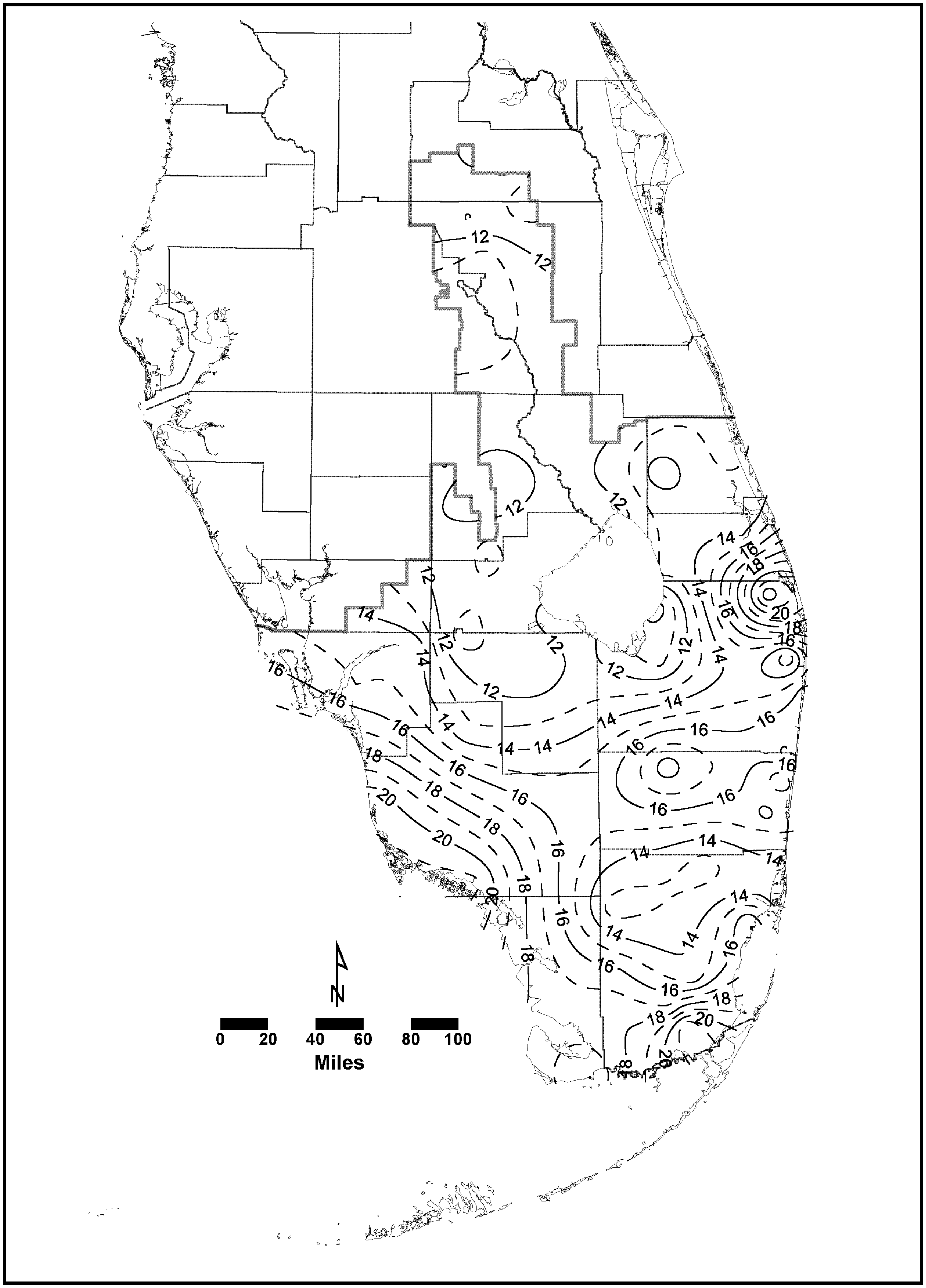


Figure 19. Three - Day Maximum Rainfall (in inches): 100-Year Return Period

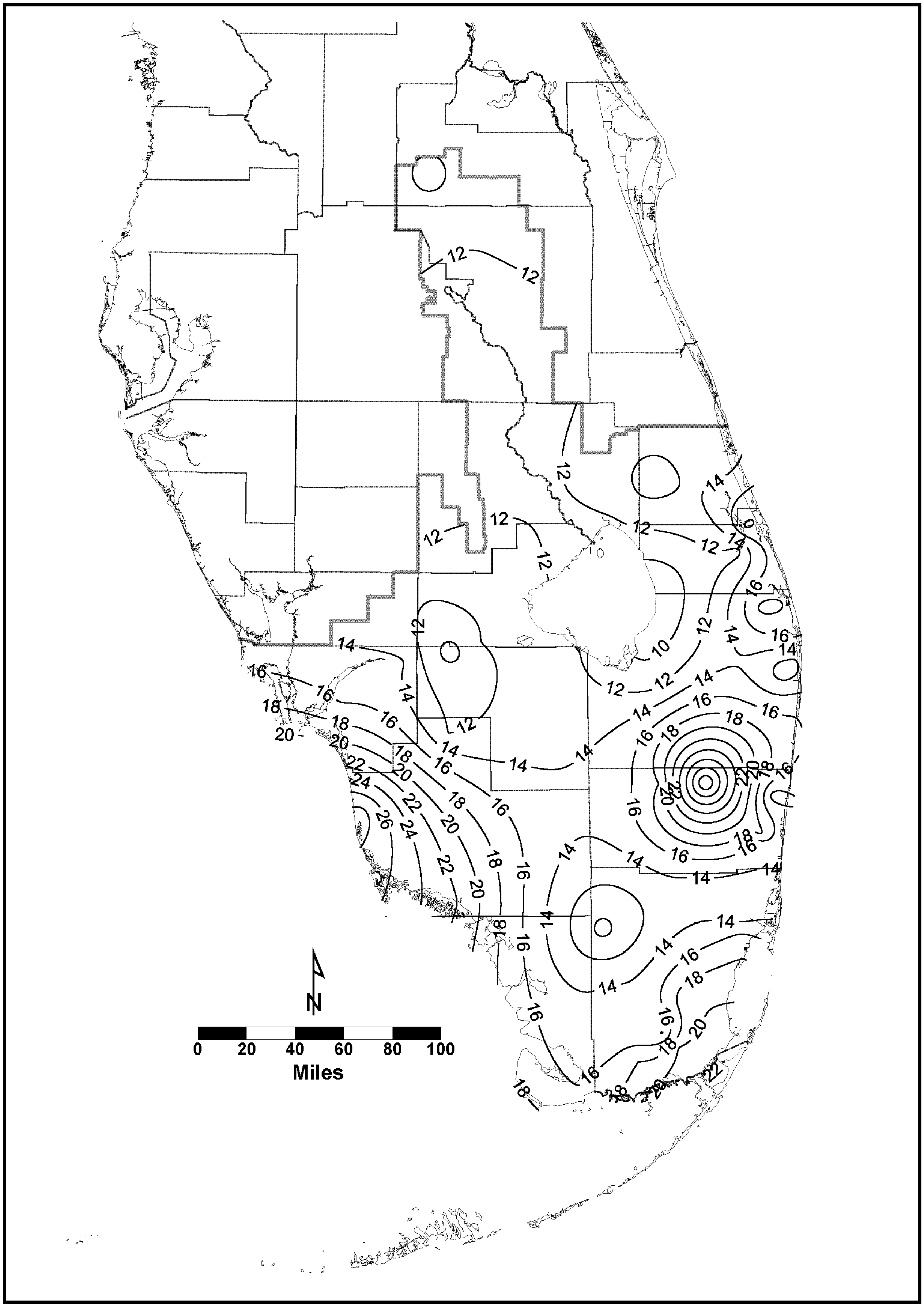


Figure 20. Three - Day Maximum Rainfall (in inches): Maximum Recorded

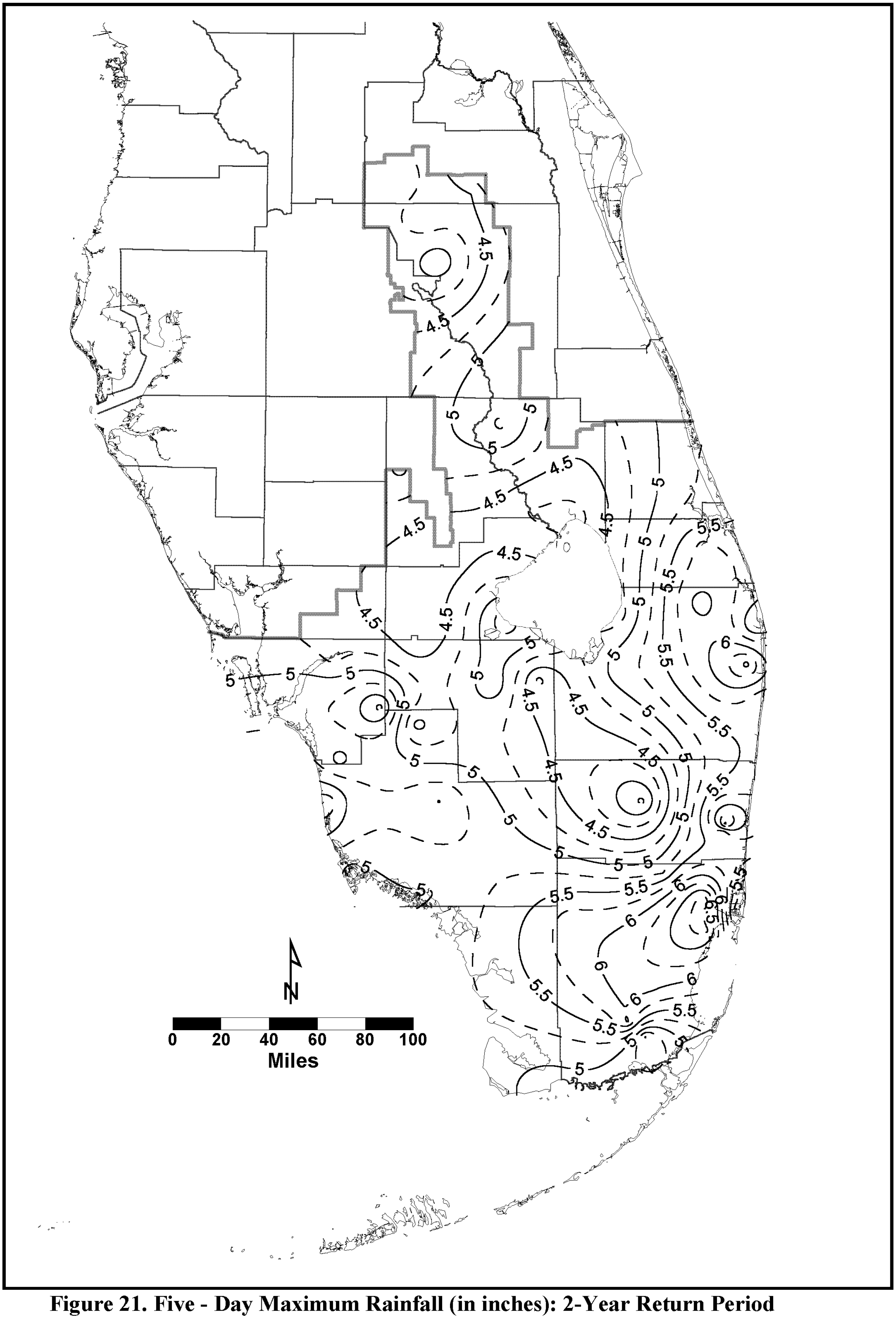


Figure 21. Five - Day Maximum Rainfall (in inches): 2-Year Return Period

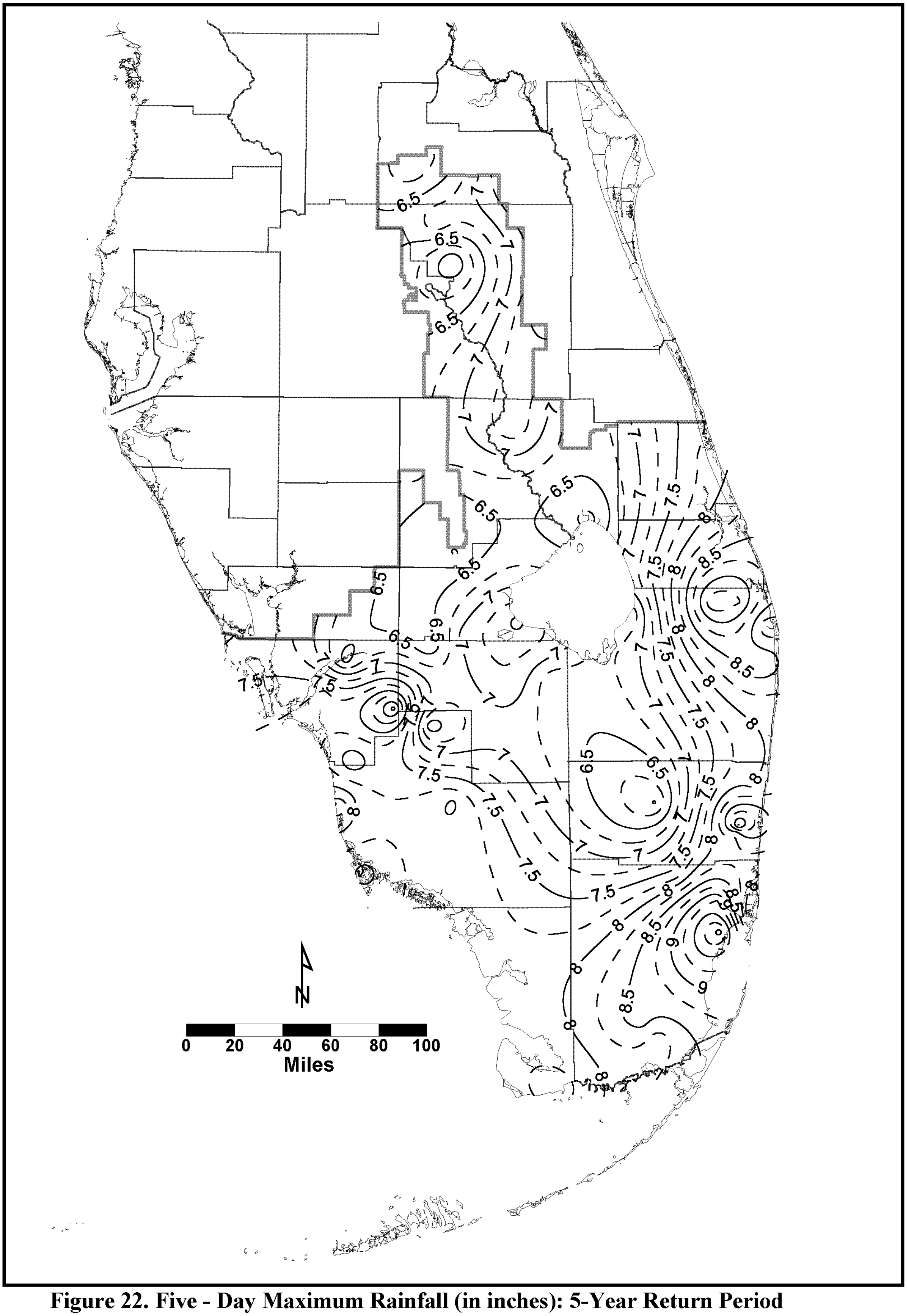


Figure 22. Five - Day Maximum Rainfall (in inches): 5-Year Return Period

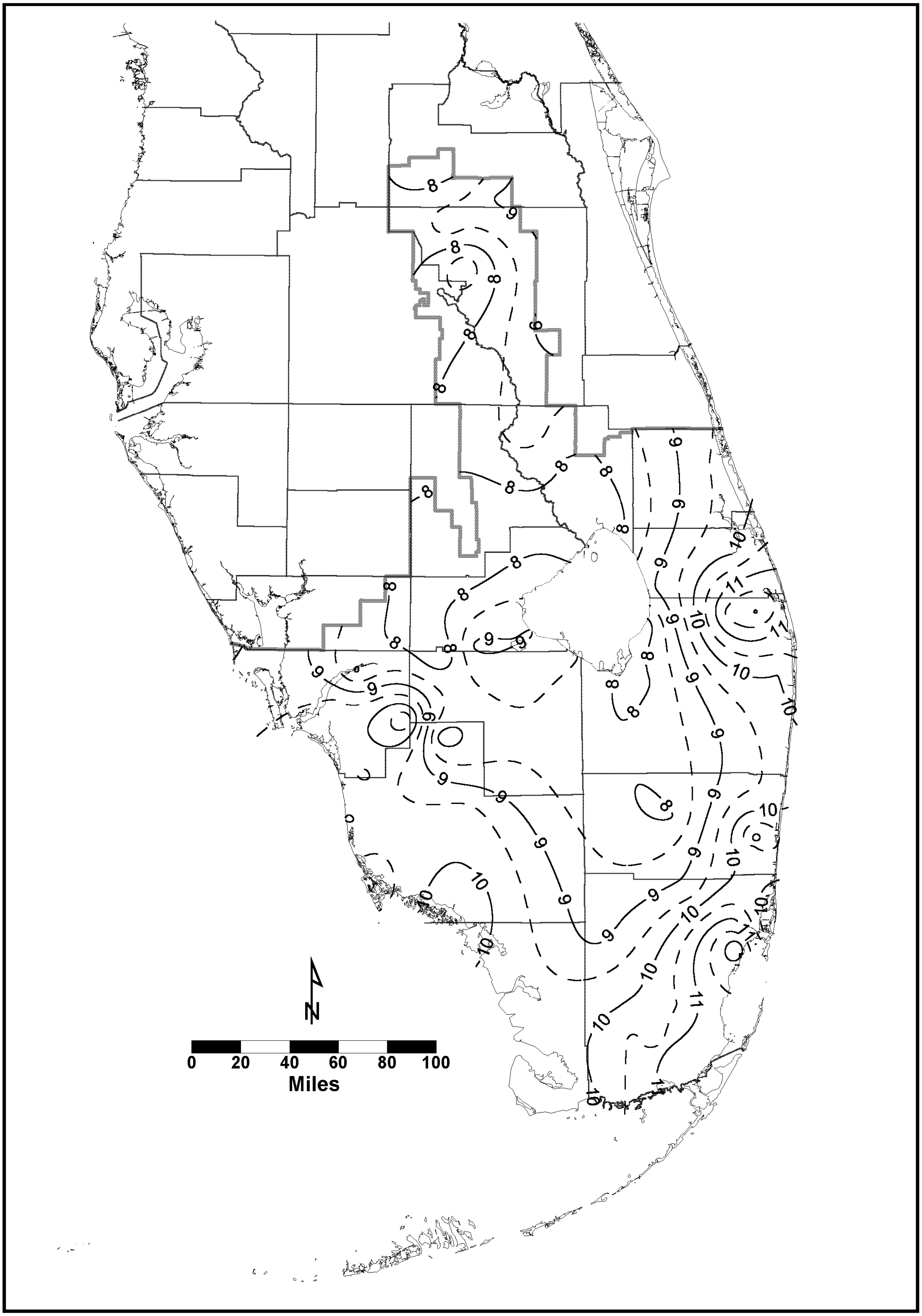


Figure 23. Five - Day Maximum Rainfall (in inches): 10-Year Return Period

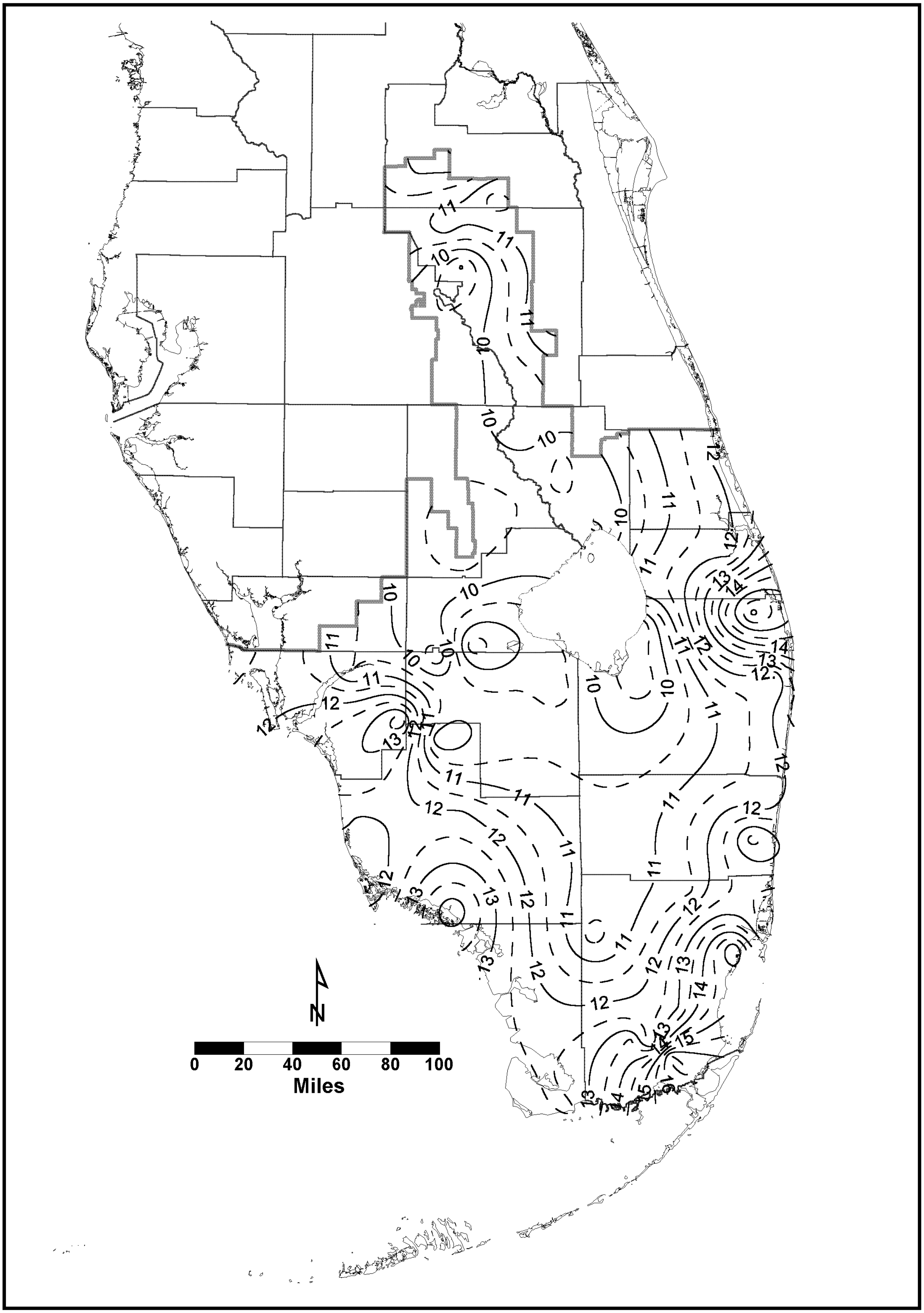


Figure 24. Five - Day Maximum Rainfall (in inches): 25-Year Return Period

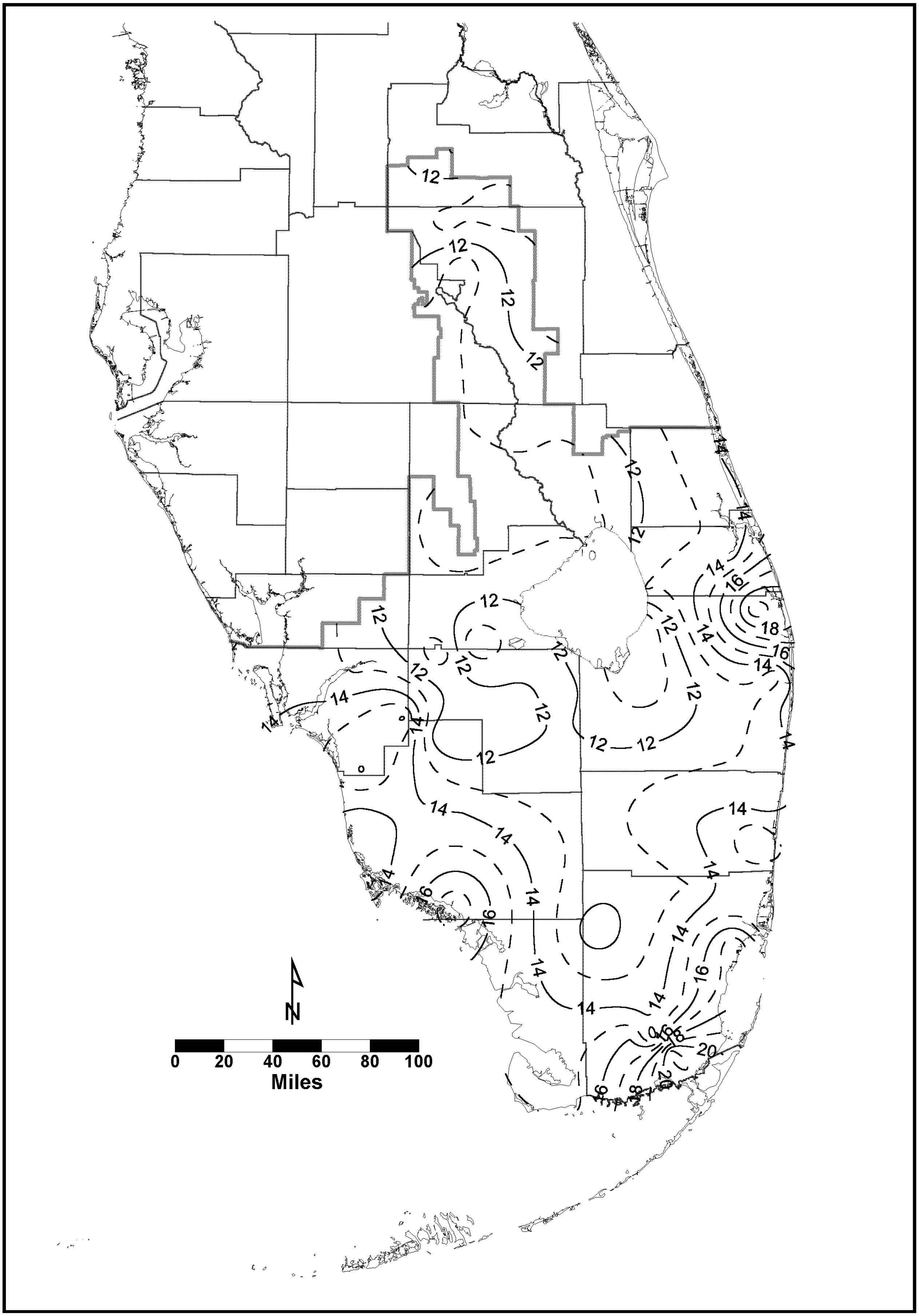


Figure 25. Five - Day Maximum Rainfall (in inches): 50-Year Return Period

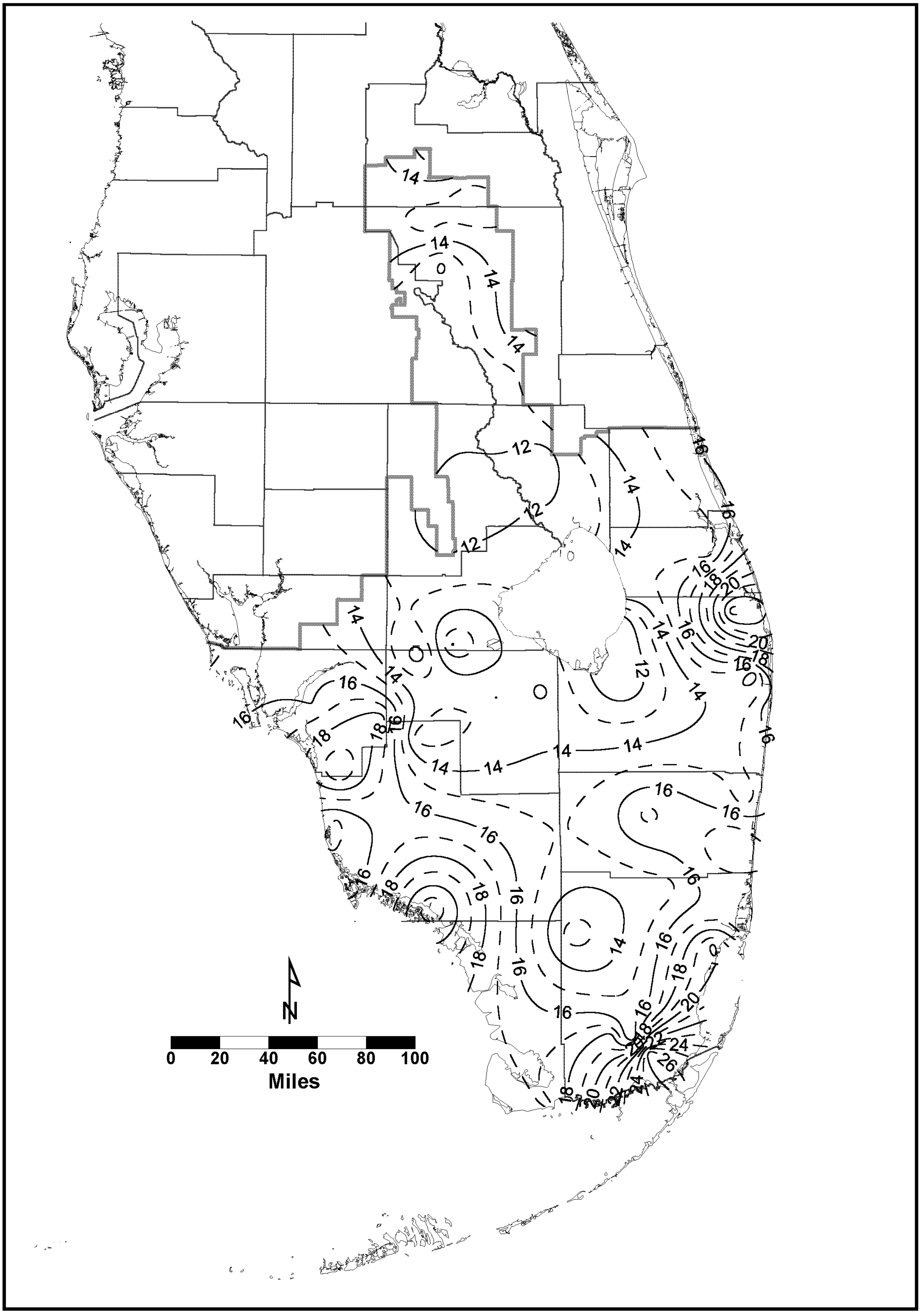


Figure 26. Five - Day Maximum Rainfall (in inches): 100-Year Return Period

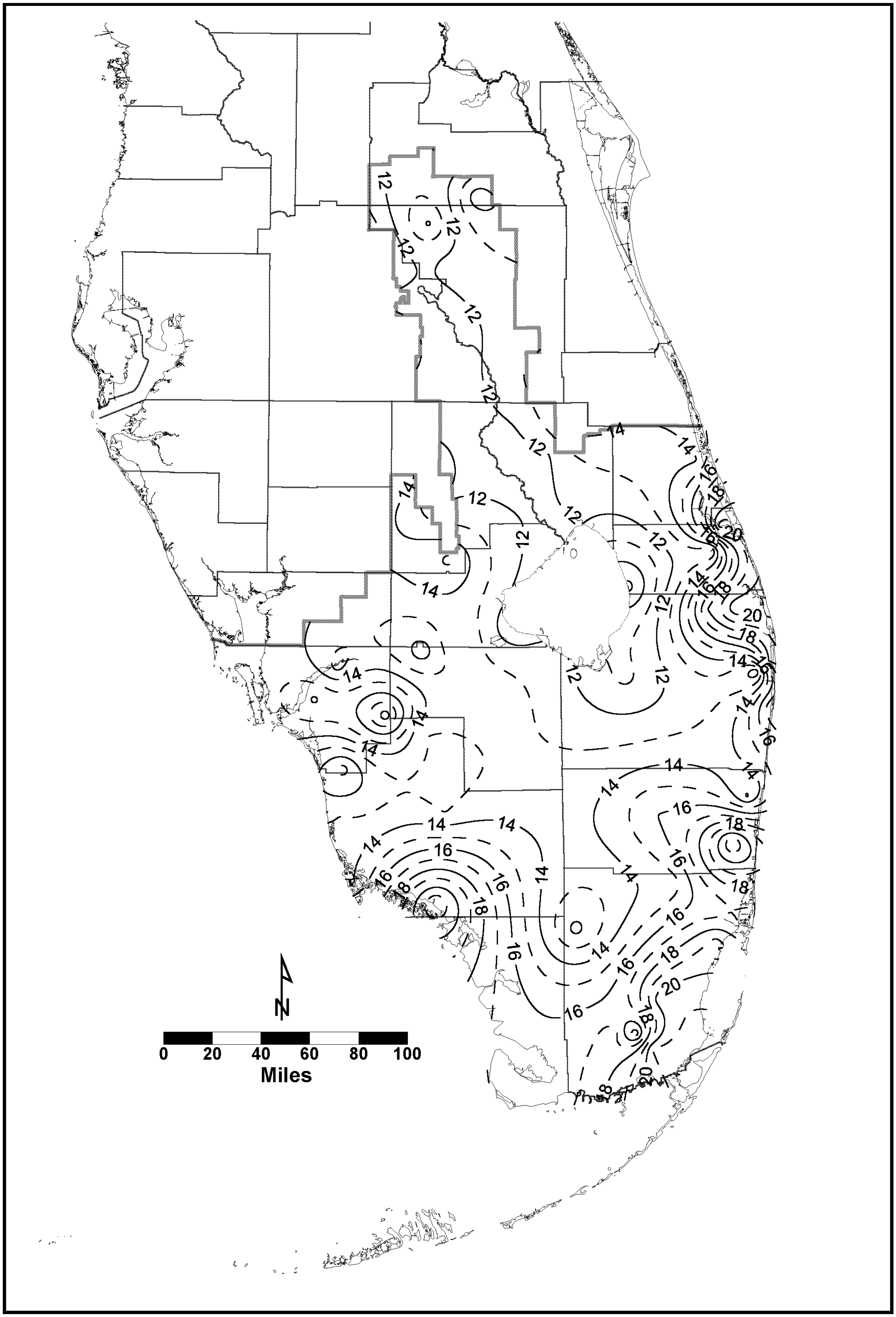


Figure 27. Five - Day Maximum Rainfall (in inches): Maximum Recorded

Comparison of Isohyetal Maps from Previous Studies

The isohyetal maps prepared in this study were compared with previous two studies published by MacVicar (1981) and Trimble (1990). This comparison was qualitative and relative. The return period of 100-year (most common) was used. Also, it is presented by three rainfall durations and parts of the three regions – east, west and north (as defined in previous section titled "Data Analysis of Maximum Recorded Rainfall" of this report) in the following paragraphs.

For 100-year return period and one-day rainfall duration, the rainfall estimates of this study were similar to both previous studies for upper eastern region. This study produced somewhat lower rainfall estimates for middle part of the eastern region compare to both previous studies. However, this study estimated higher rainfall for lower eastern region than other two studies. Higher rainfall estimates were also produced in this study than both other studies for middle and lower parts of western region. Similar rainfall estimates were generated for upper western region by all the three studies. The rainfall estimates in this study were similar to Trimble study for upper northern region, but they were lower than MacVicar study. This study produced higher rainfall estimates than both the other studies for lower northern region.

For 100-year return period and three-day rainfall duration, the rainfall estimates were similar to MacVicar study for upper eastern region, but they were slightly higher than Trimble study. For middle part of the eastern region, this study produced smaller estimates than other two studies. Higher rainfall estimates were computed in this study than both other studies for lower eastern region. The rainfall estimates were higher in this study than other two studies for middle and lower western region. All the three studies estimated similar rainfall depths for upper western region. The rainfall estimates in this study were slightly higher than Trimble study for upper northern region, but they were lower than MacVicar study. This study produced higher rainfall estimates than both the other studies for lower northern region.

For 100-year return period and five-day rainfall duration, this study estimated slightly higher rainfall than MacVicar study for upper eastern region. Trimble study did not present isohyetal maps for the five-day rainfall duration. However, this study estimated lower rainfall than MacVicar study for middle eastern region. Higher rainfall estimates were computed in this study than MacVicar study for lower eastern region. Both the studies estimated similar rainfall depths for middle and lower western region. This study produced somewhat higher rainfall estimates compare to the previous study for upper western region. The rainfall estimates in this study were slightly lower than Trimble study for upper and lower northern region.

In summary, rainfall estimated in this study were higher in the middle and lower parts of the western region and lower part of the eastern region. Whereas, the rainfall estimates were lower in the middle portion of the eastern region. The differences in rainfall estimates from pervious two studies were expected. The reasons for these differences are several. However, some of the differences could be attributed to the following: (a) methodology used in selecting gage stations for the analysis, which used the gage records with the highest maximum recorded rainfall from their respective period-of-record; (b) clustering of nearby gage records where dense rain-gage network exist; (c) use of longer period-of-record gage records which included high magnitude rainfall events which occurred during the 1990 decade and (d) selection of a probability distribution used in rainfall estimation at each gage station.

SUMMARY AND CONCLUSIONS

For three rainfall durations, the maximum-recorded rainfall amounts were obtained for each available gage record from its the period-of-record for the last 100 years. The rainfall amounts from hurricanes and tropical storms during the last 100 years were obtained and analyzed. Frequency analysis of the daily rainfall maxima was performed. In the study, the rainfall depths were estimated for six return periods and three rainfall durations. The return periods were two-, five-, 10-, 25-, 50-, and 100-year and the rainfall durations were one-day, three-day and five-day periods. Based on the spatial characteristics, the estimated rainfall depths were mapped. The objective of this study was to update the existing rainfall frequency analysis by using the up-to-date data and detailed analysis, and to prepare isohyetal maps.

The daily rainfall data retrieved from the DBHYDRO (a computer database at the District headquarters) was used. One maximum rainfall value for each gage record was obtained from its period-of-record. A total of 973 gage records were used to determine the maximum rainfall values. The northern, eastern, and western regions used 227, 499 and 247 gage records, respectively. Three sets of rainfall gage records, for one-day, three-day, and five-day durations, were used in determining the maximum rainfall over their respective period-of record. The maximum recorded rainfall varied between four and 18 inches for the one-day duration. The maximum rainfall ranged from six to 20 inches for the three-day duration. While, the maximum rainfall was recorded between eight and 22 inches for the five-day duration.

Central and South Florida was affected by 38 hurricanes and 23 tropical storms from 1900 to 1999. A total of 61 rainfall events occurred due to hurricanes or tropical storms in the last 100 years (from 1900 to 1999). The maximum rainfall events occurred in August, September and October, and they were 19, 29, and 29 percent respectively. These events generated rainfall with one- to 14-day durations. A maximum of 11 events was recorded during the decade of 1940 (i.e., between 1940 to 1949). However, a minimum of two events occurred during the decade of 1970. The average of maximum rainfall and standard deviation for these events were 11.5 and 5.0 inches, respectively. The range of maximum rainfall for 59 events was 23.5 and 2.0 inches. Frequency analysis of these rainfall events indicates that 5, 25, 50, 75 and 85 percent of these events produced the rainfall amounts greater than 22.0, 16.0, 13.0, 10.0 and 8.0 inches, respectively.

The selected gage records were grouped into clusters based on their x and y coordinates (i.e., state plane system for geographic location). Each cluster was developed individually to include all the gage records that were located one to three miles apart from each other. The clusters had varied numbers of gage records, and they varied from one to eight gage records in a cluster. Subsequently, each cluster was identified by one unique dbkey representing one gage station.

For frequency analysis, a procedure was developed to select a set of stations (i.e., clusters) for each of the three geographic regions of the District. However, the areas located within the Key West islands and Lake Okeechobee were excluded. A significant number of the selected stations has a time series of daily rainfall of more than 50 years. For the selected stations, the annual or partial duration series were constructed. A total of 86, 66 and 65 stations were selected for one-day, three-day and five-day durations, respectively. Seven probability distributions were applied to the annual or partial annual series of each selected station. The distributions were Normal, two-parameter Log Normal, three-parameter Log Normal, two-parameter Gamma, three-parameter Gamma, Weibull and Log Pearson Type III. Based on the established best-fit criteria, a probability distribution was selected to fit the annual series data of each selected station. The results provided the rainfall depths for various return periods at each station. This process was applied to all the three rainfall durations (i.e., one-day, three-day, and five-day).

The results from the frequency analysis were presented. They showed the rainfall estimates for six return periods and three durations. The minimum rainfall estimates for 100-year return period were 6.0, 8.9 and 11.0 inches for one-day, three-day and five-day durations, respectively. The maximum rainfall estimates for 100-year return period were 21.0, 22.8 and 26.6 inches for one-day, three-day and five-day durations, respectively. Several maps showing contours of rainfall depths (isohyetal) for various return periods and durations were prepared using the Kriging interpolation method.

Daily rainfall data exhibited significantly larger temporal and spatial variability compared to monthly or annual rainfall data. The annual or partial duration time series provide trends and pattern of the extreme events. The mathematical fitting of the annual time series to a standard probability distribution would usually introduce some smoothing effect. More often, this smoothing effect generates lower estimates of the high magnitude events and higher estimates of the small magnitude events.

The parameters of the selected probability distribution are estimated from the historical data series. In general, the variance of a parameter estimate is a decreasing function of the sample size. The larger the sample, the smaller the variance of the parameter estimate. This means that as the number of years of record increases, the probability of making an error, greater than a given value, decreases. Therefore, for larger period-of-record, the parameter estimate would be closer to its true value. In addition, the estimates of rainfall at the lower probability levels (such as probability of 0.01) in the tail of the probability distribution are more sensitive to these parameter estimates. For a given period of record, this would mean that as the probability levels decrease the variance of the rainfall estimates increases. In other words, when 50 years of annual series at a given station are fitted to a selected probability distribution, the rainfall estimate at probability level of 0.5 (two-year return period) is closer to its true value, whereas rainfall estimate at probability level of 0.01 (100-year return period) has a larger variance. However, this variance and its associated reliability can be estimated by applying stochastic models. In order to reduce the variance (of rainfall estimate at probability level of 0.01), a longer period-of-record (than the existing one) is needed for the frequency analysis.

The spatial variability of the rainfall estimates, obtained from the point frequency analysis of the daily rainfall data, does not provide any systematic trends or patterns. The reason for this phenomenon can be explained by : (a) significantly large spatial variability in the rainfall exists due to complex meteorological related activities; and (b) inability to capture the rainfall variability due to the relatively low density of the current rain gage network. However, the spatial variability of the daily rainfall data could be studied with the aid of radar-generated rainfall estimates. The potential to use NEXRAD and/or Doppler radar technology for spatial analysis of the daily rainfall should be assessed and evaluated.

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